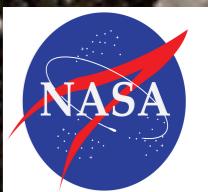


Planet Formation in Star-Forming Regions

: from the Solar System to Other Worlds

Yasuhiro Hasegawa

Jet Propulsion Laboratory,
California Institute of Technology



First Stage

\sim micron \sim mm

Second Stage

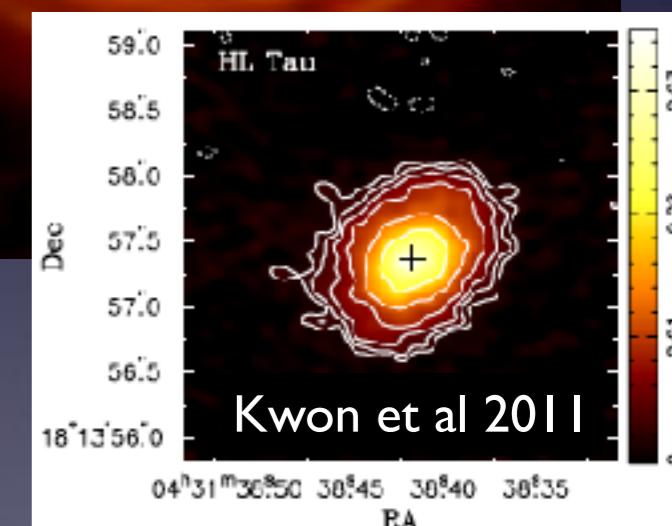
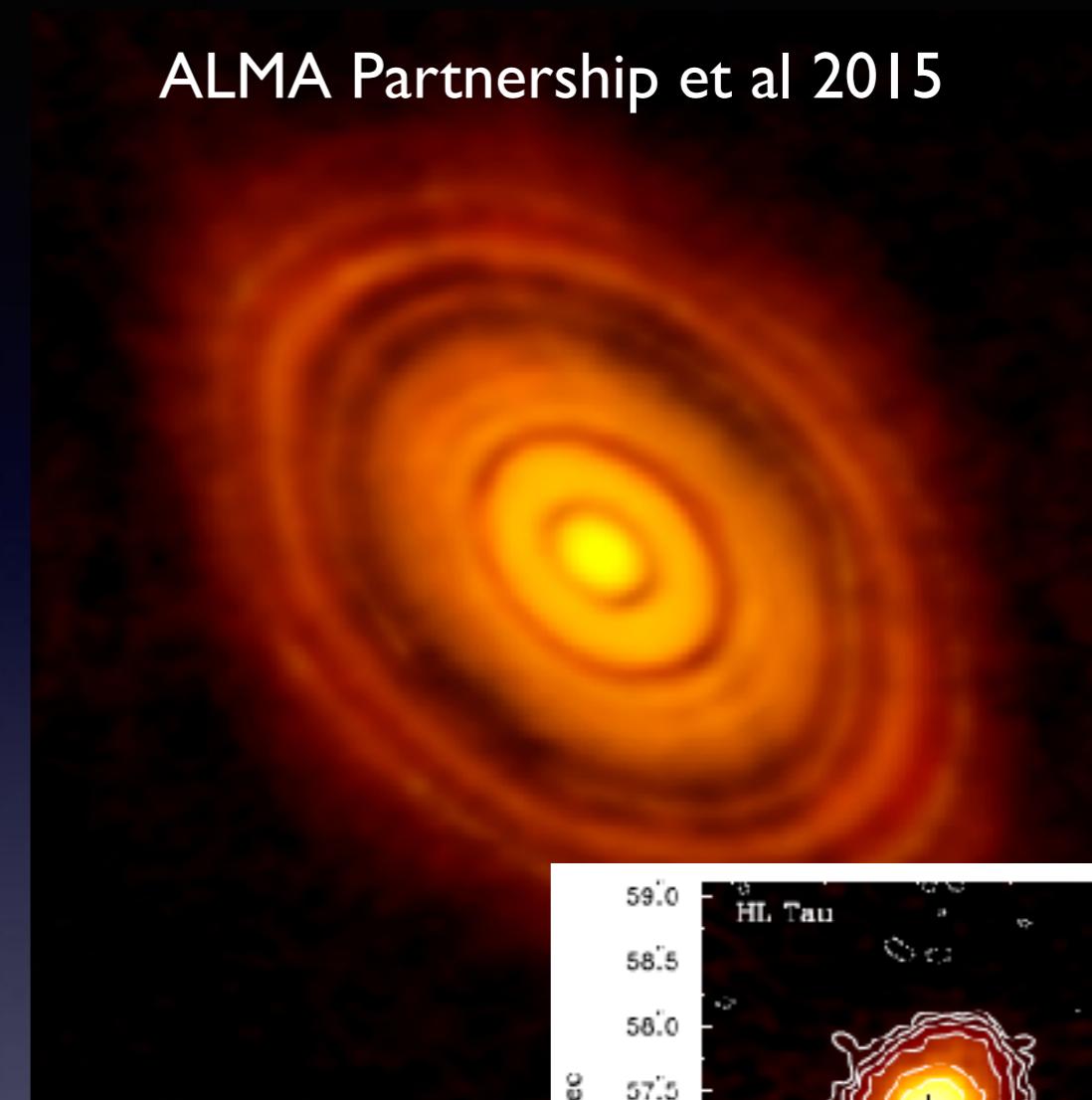
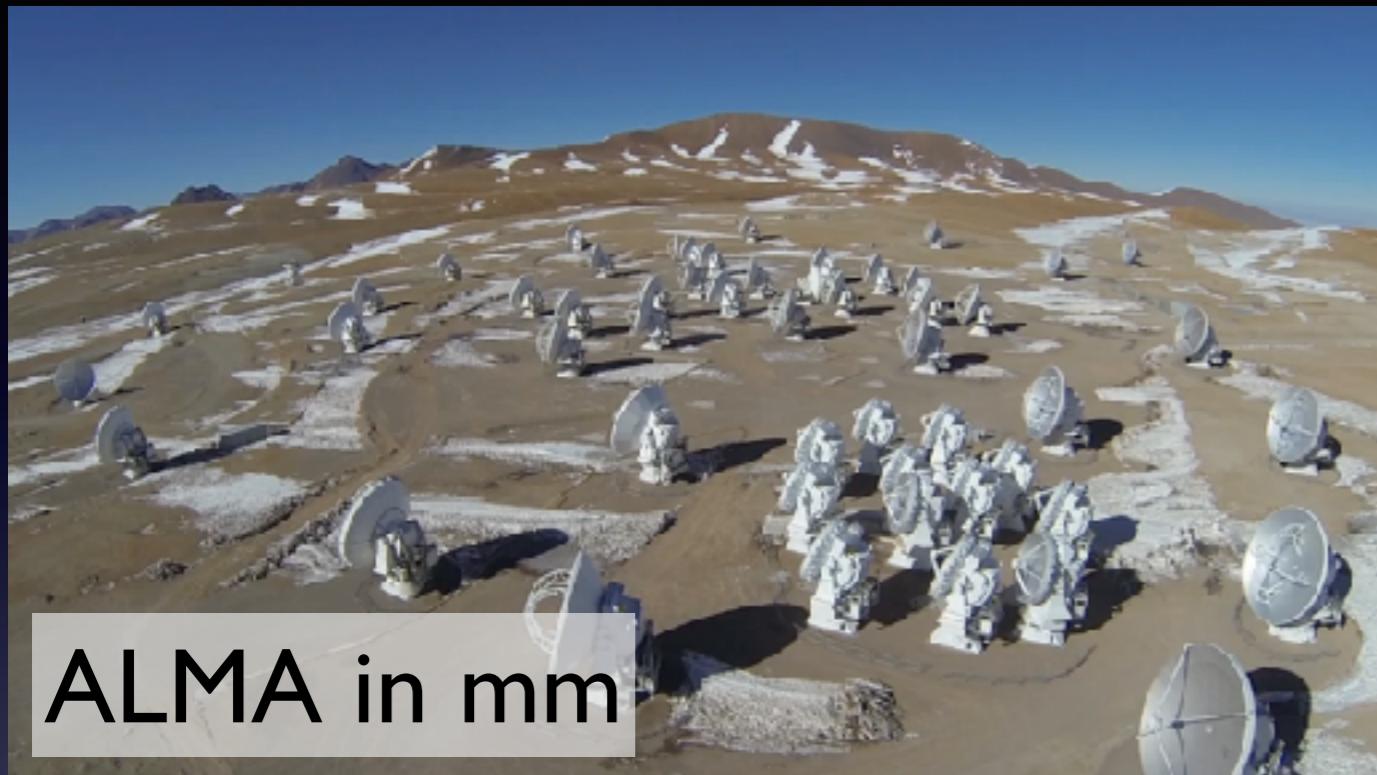
\sim m

Third Stage

\sim km $\sim 10^3$ km

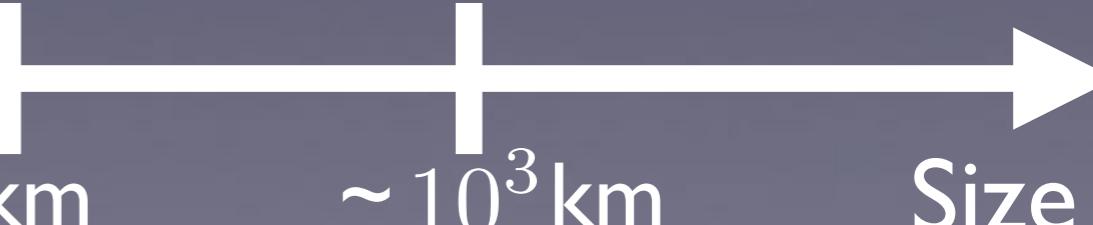
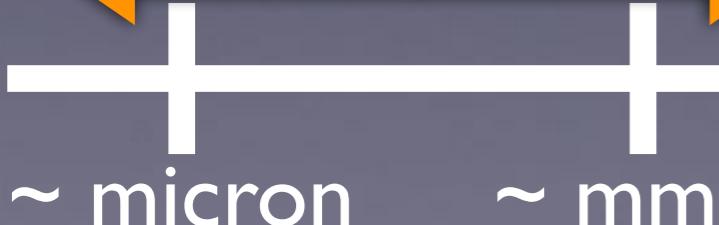
Size

I. Evolution in Astronomical Disk Observations



We can **see** planet-forming regions

First Stage



JWST is coming soon

Size

2. Evolution in Space Engineering & Lab Experiments



Rosetta

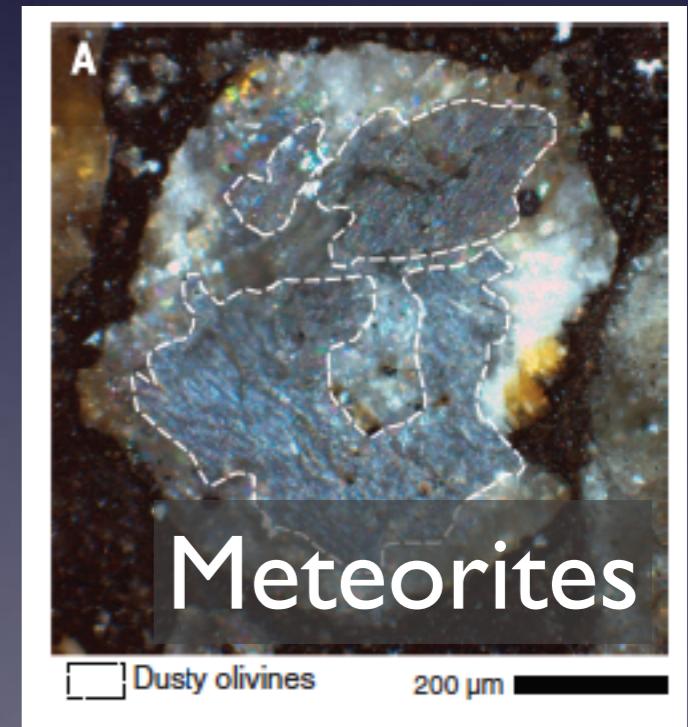


OSIRIS-REx



Hayabusa

We can **touch**
planet-forming
materials



Meteorites

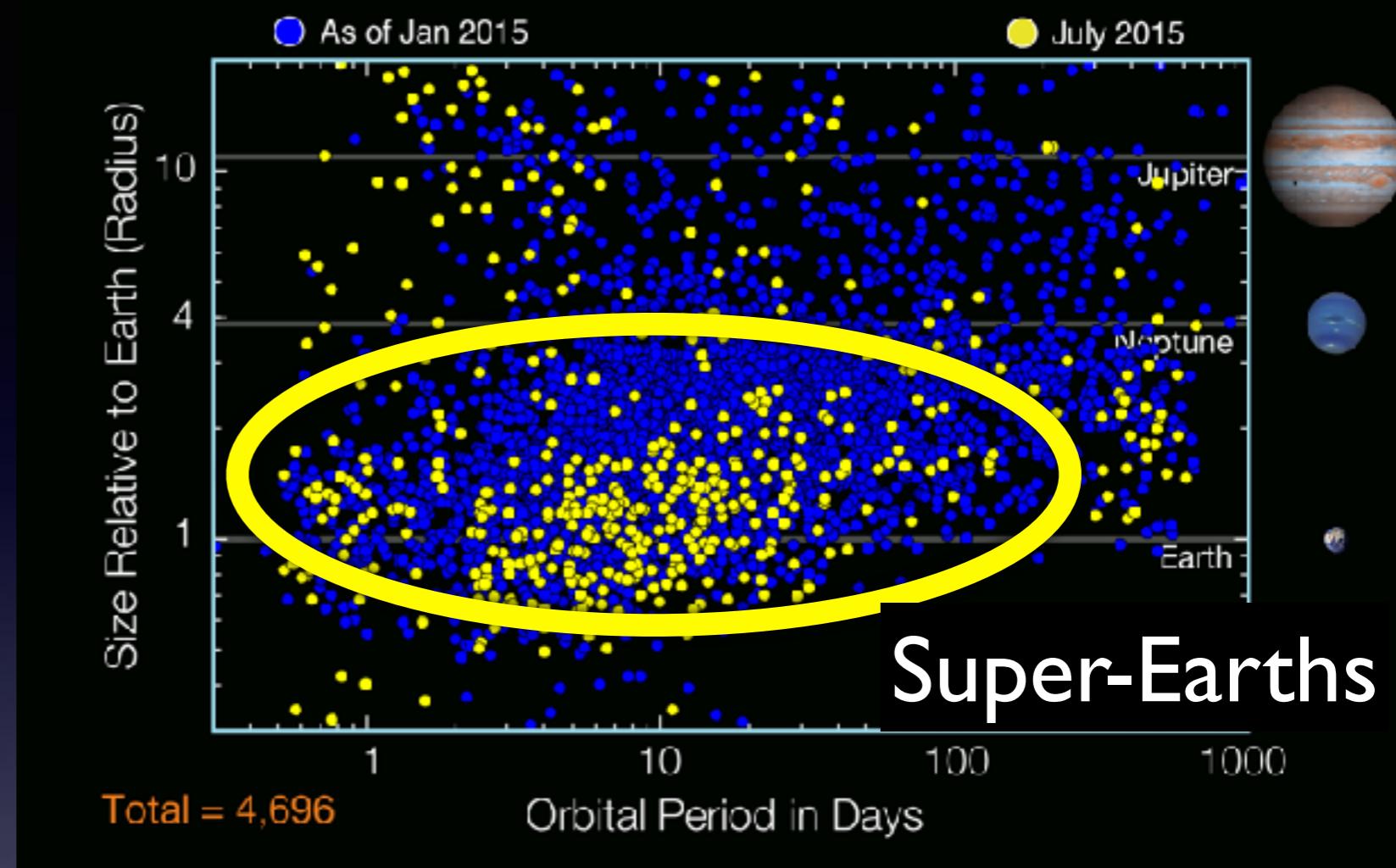
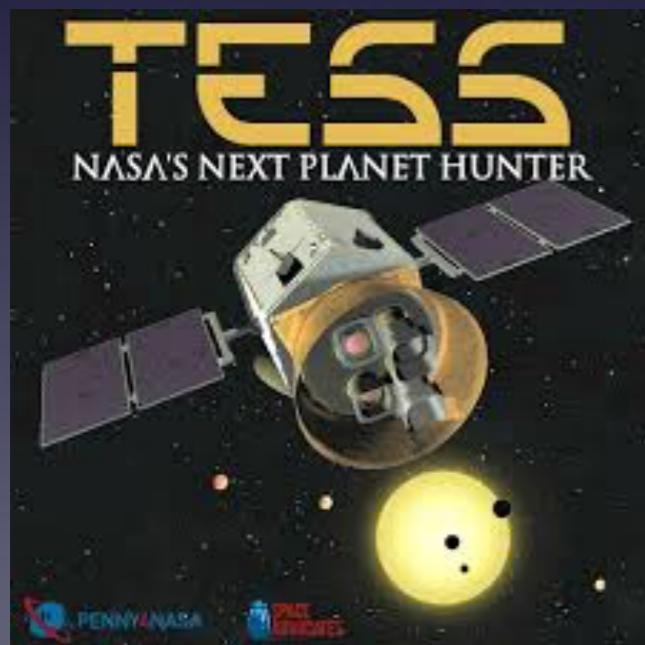
Second Stage

↔
~ micron ~ mm

↔
~ m ~ km

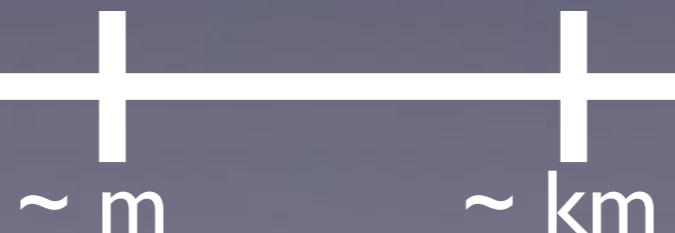
↔
~ 10^3 km Size

3. Evolution in the Number of Known (exo)Planets



We can **characterize** (exo)planetary systems

Third Stage



Planet formation:
Long journey
from dust to planets

Golden era of
(exo)planetary
sciences

A Comprehensive Examination of Planet Formation
Covering the Full Size Range

First Stage

Second Stage

Third Stage


~ micron


~ mm

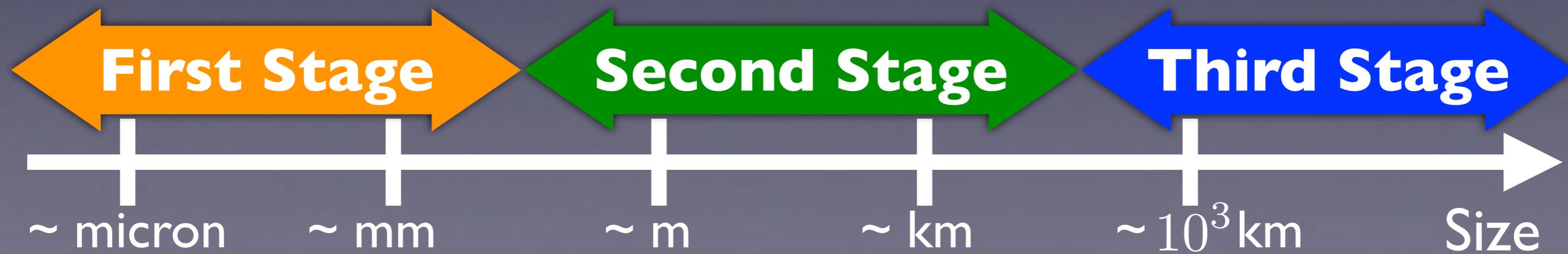

~ m


~ km

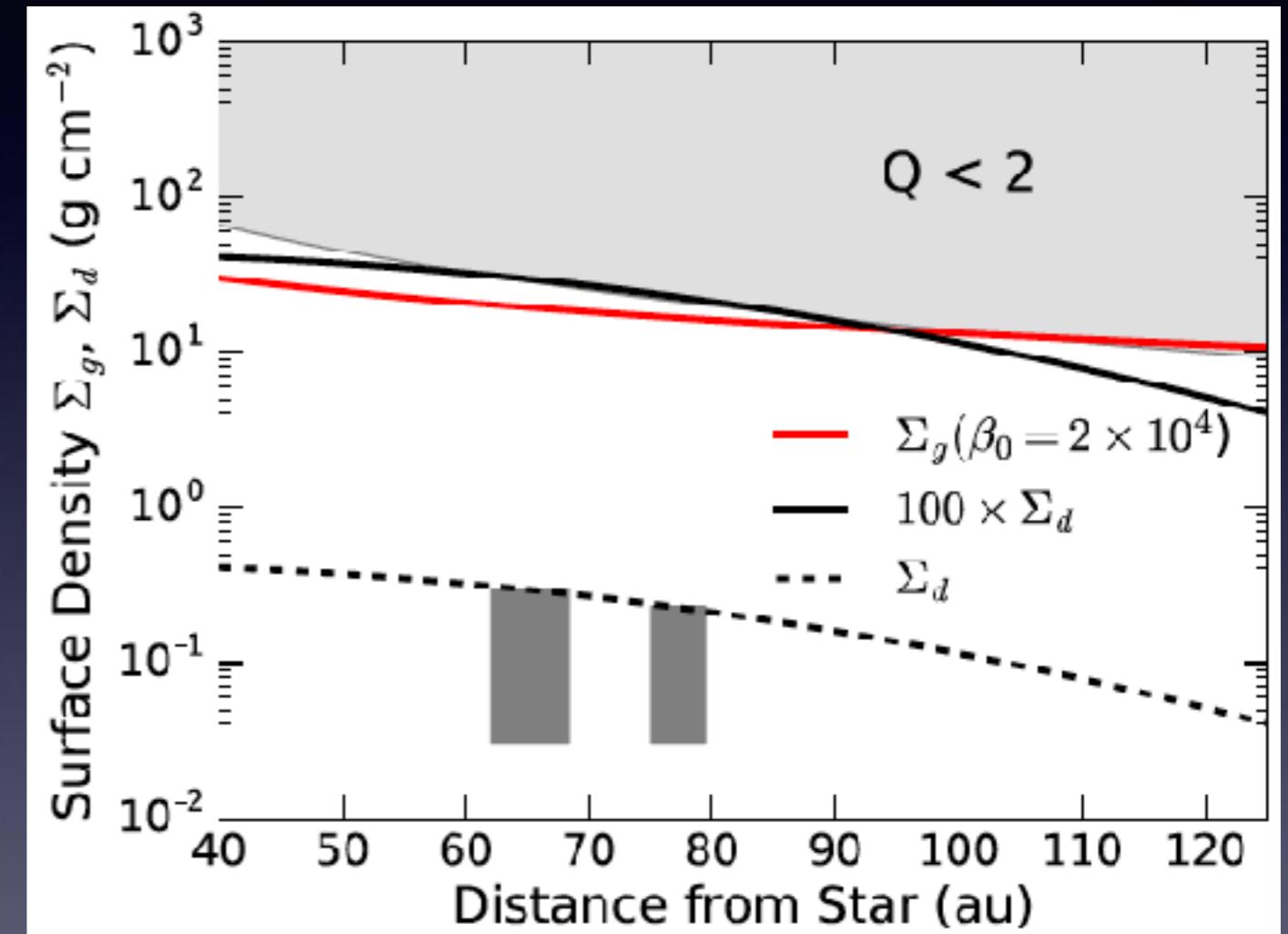
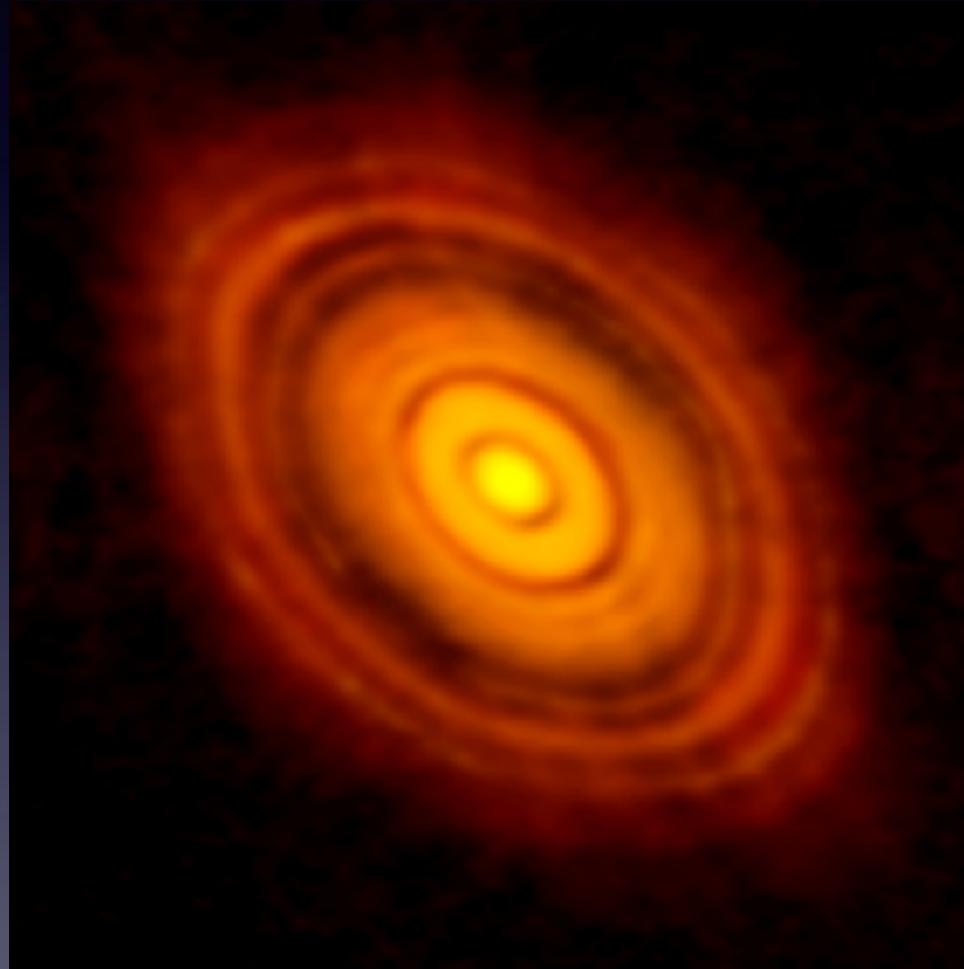

~ 10^3 km

Size

A Comprehensive Examination of Planet Formation



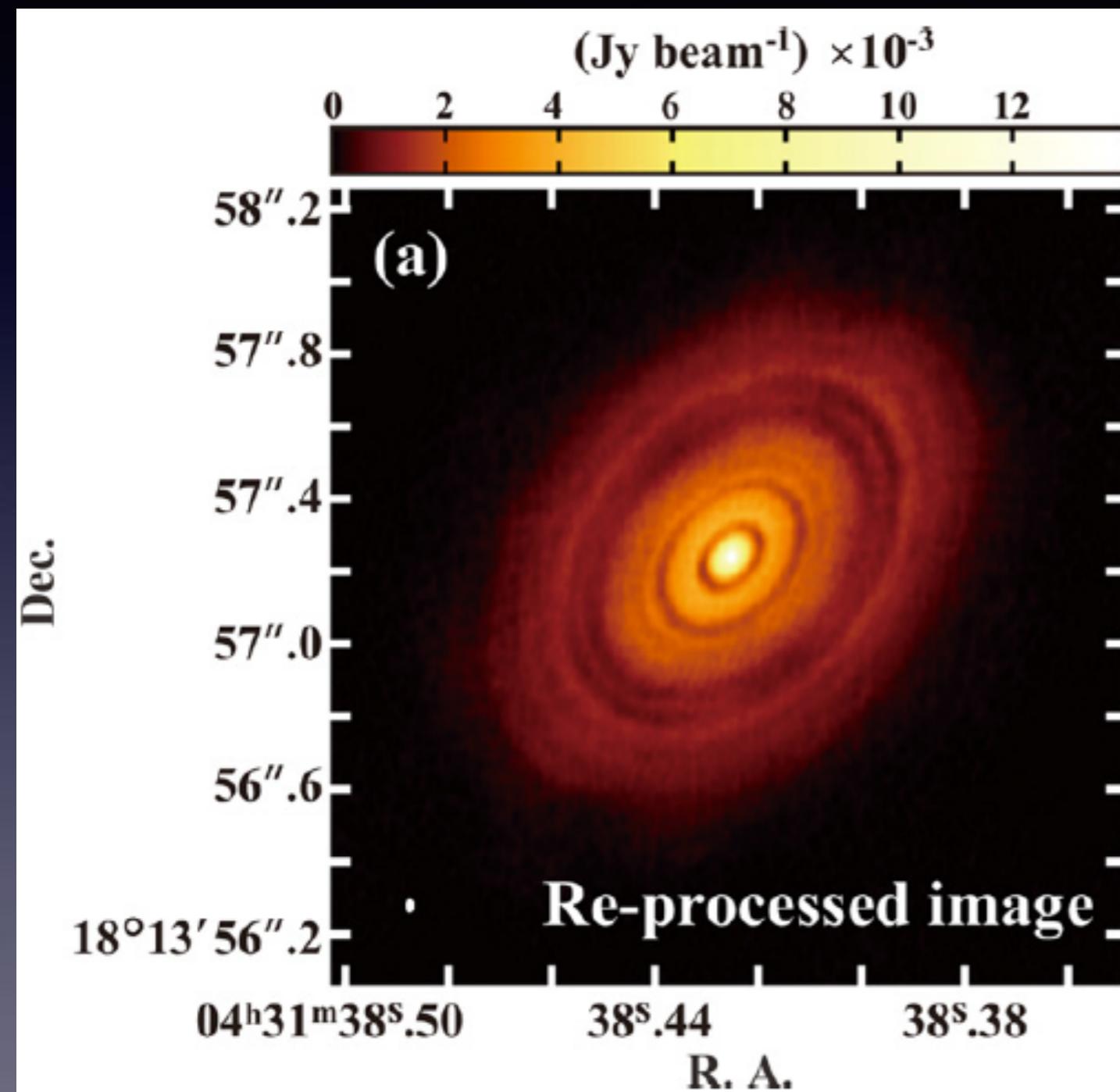
Magnetically Induced Disk Winds and Transport in the HL Tau Disk



in collaboration with
Satoshi Okuzumi (Tokyo Tech), Mario Flock (MPIA), Neal Turner (JPL)

Astonishing ALMA Images of HL Tau

ALMA Partnership et al 2015,
also see Akiyama YH et al 2016



HL Tau : a Class I/II YSO
: ~ 140 pc (< 1 Myrs)

Nearly concentric
multiple gaps in
the dust thermal emission

Potential signature of
planet formation

The origin of observed gaps is not identified yet!!

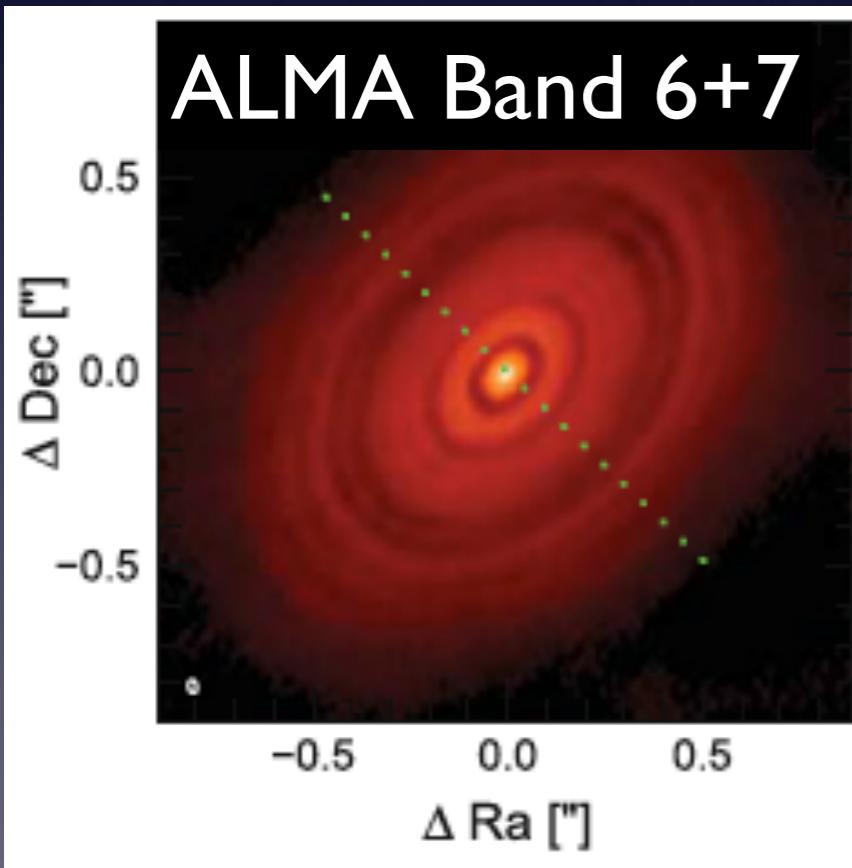
Global Properties of the HL Tau Disk

Disk accretion rate $\simeq 10^{-7} - 10^{-6} M_{\odot} \text{ yr}^{-1}$

Hayashi et al 1993, Beck et al 2010

Global diffusion coefficient : $\alpha_{\text{GL}} \simeq 10^{-2} - 10^{-1}$

=> can be explained by MRI and MHD turbulence



ALMA Partnership et al 2015
also see Akiyama et al 2016

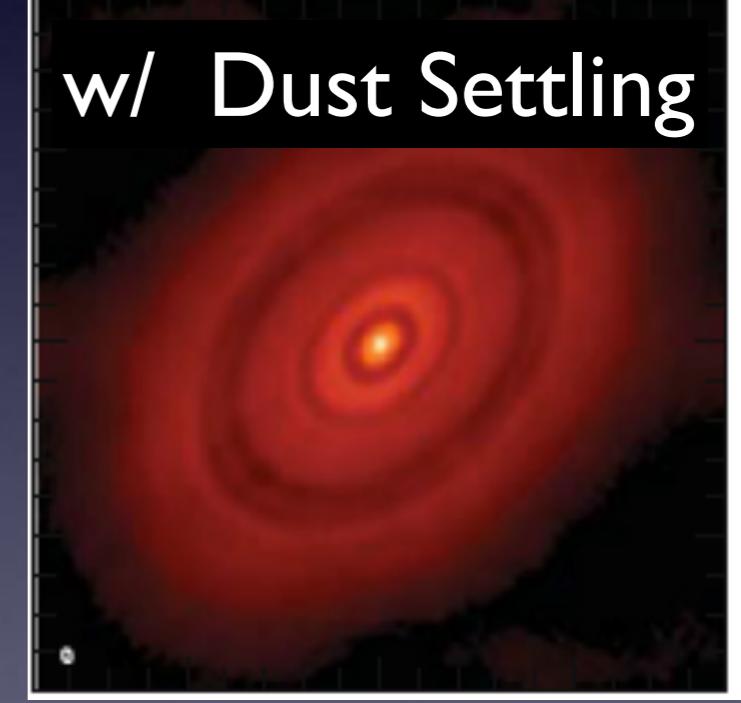
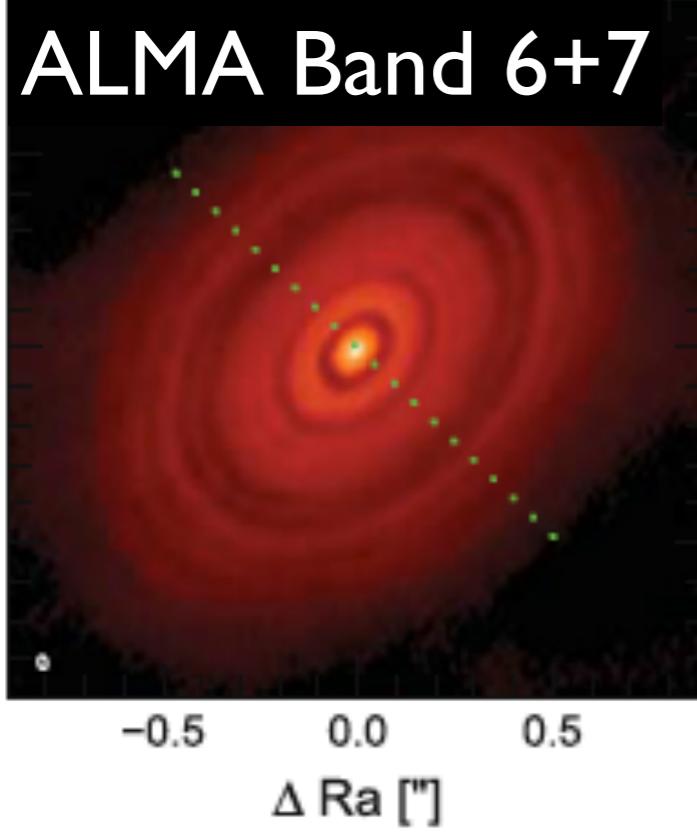
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Pinte et al 2016

Vertical dust height: $\sim 1 \text{ au}$ at $r = 100 \text{ au}$
Local diffusion coefficient: $\alpha_{\text{LC}} \sim 10^{-4}$

Global Properties of the HL Tau Disk

Disk accretion rate $\simeq 10^{-7} - 10^{-6} M_{\odot} \text{ yr}^{-1}$

Hayashi et al 1993, Beck et al 2010

Global diffusion coefficient : $\alpha_{\text{GL}} \simeq 10^{-2} - 10^{-1}$

I) How does the HL Tau disk
keep a high disk accretion rate
without exciting local turbulence??

2) Why can the HL Tau disk avoid GI??

$\Delta \text{Ra} ["]$

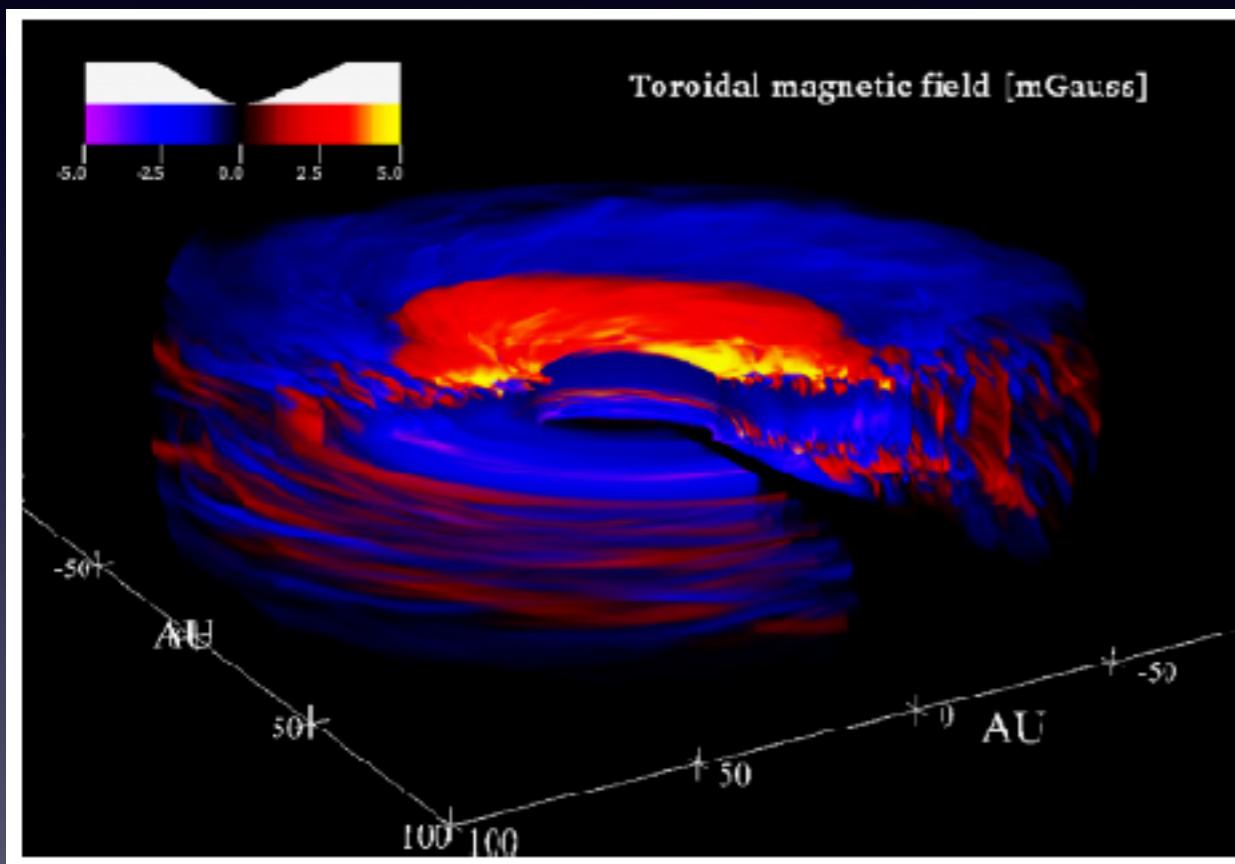
Pinte et al 2016

Vertical dust height: $\sim 1 \text{ au}$ at $r = 100 \text{ au}$
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Magnetically Driven Disk Accretion

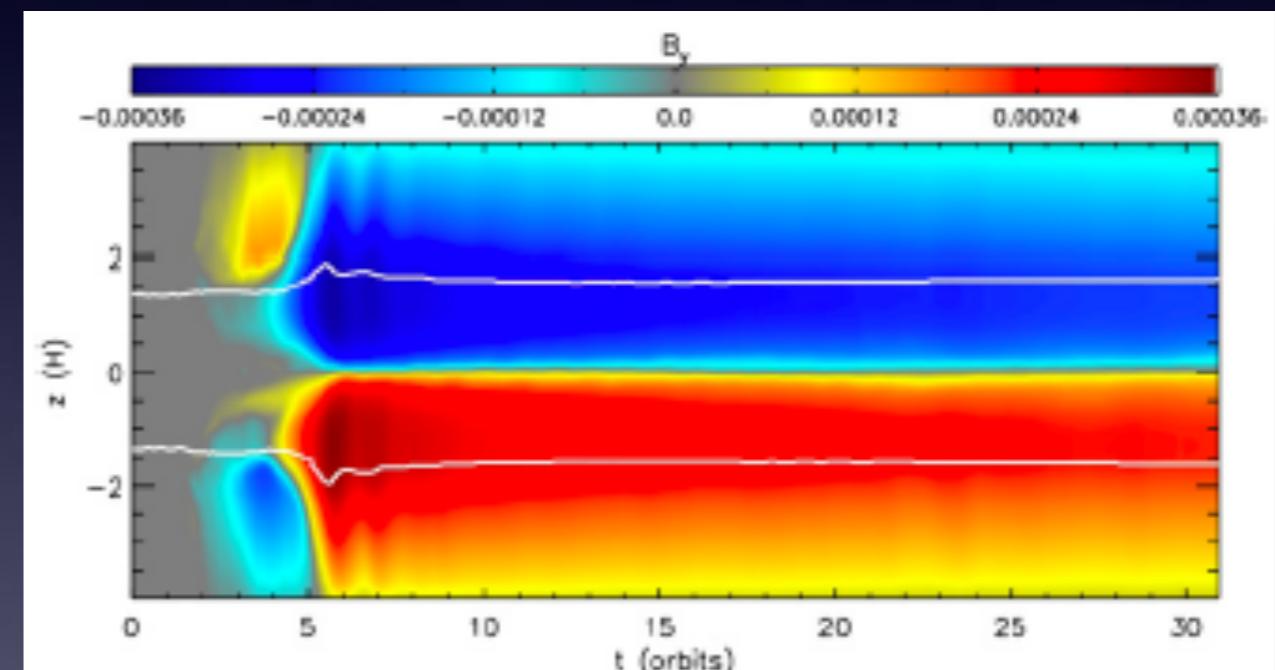
e.g., Armitage et al 2011, Bai & Stone 2013, Turner et al 2014, Suzuki et al 2016

Magnetized Turbulence

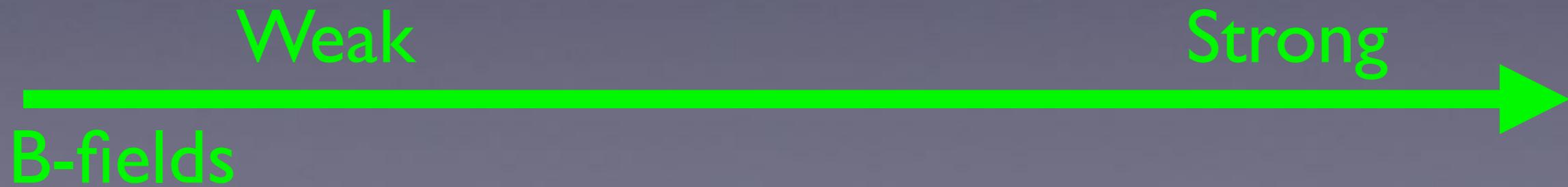


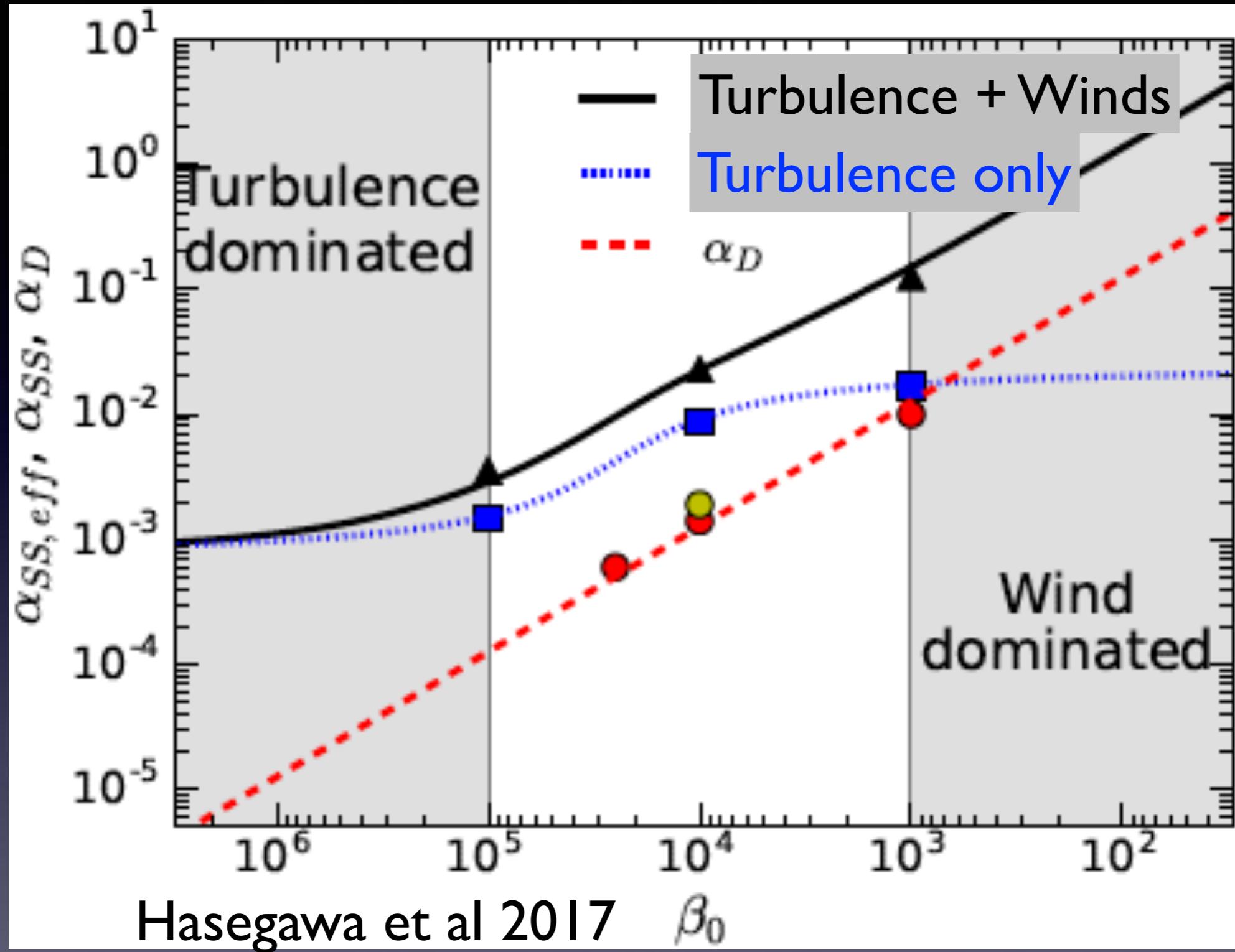
Flock et al 2015

Magnetically Induced Disk Winds



Simon et al 2013





α_D : vertical mixing of dust

Weak

B-fields

β_0 : the plasma beta

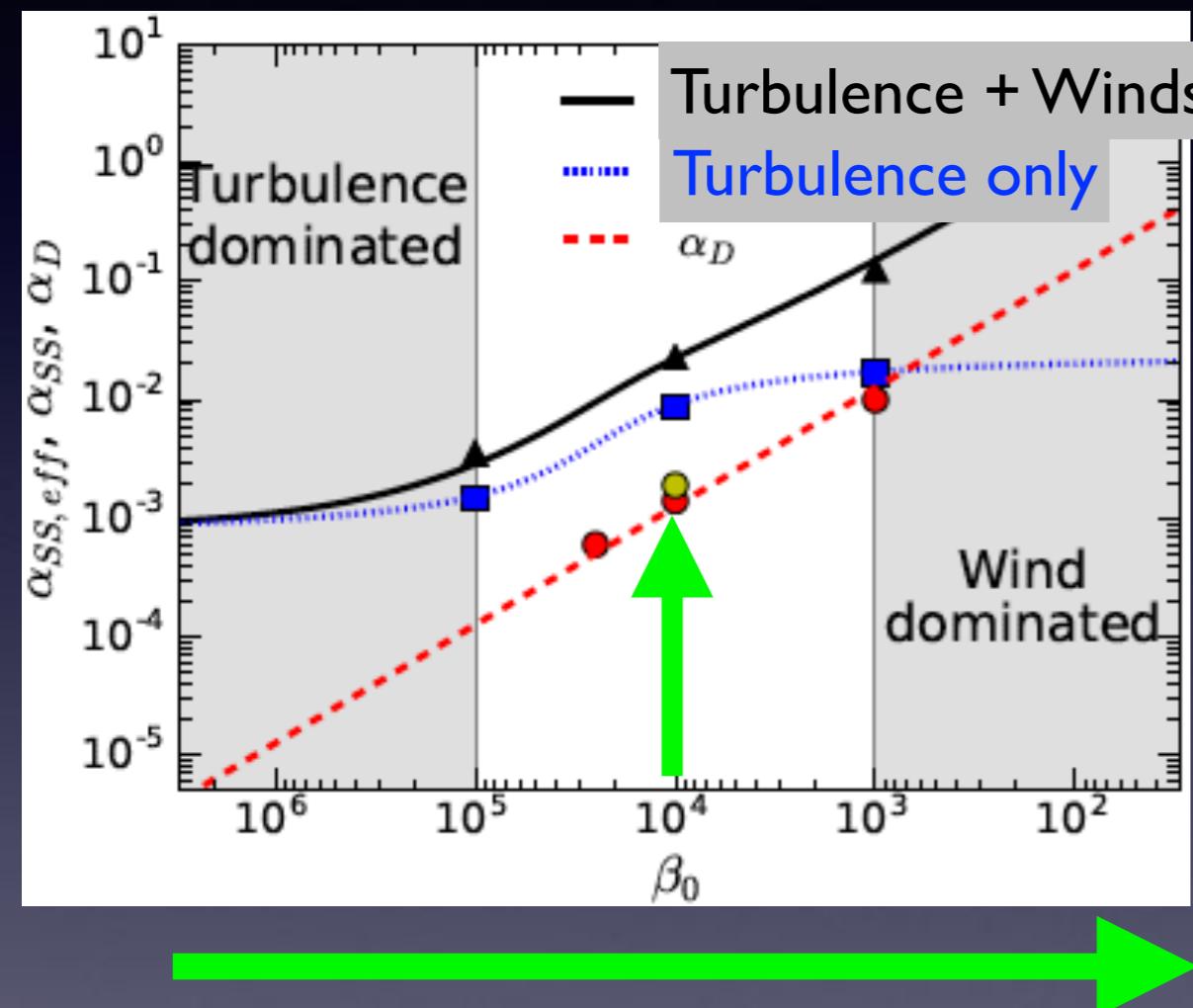
Strong

Simulation results from Simon et al 2013, Zhu et al 2015 are used

Given that

$$\dot{M}, c_s^2 (\propto T_d), \Omega (\propto \sqrt{M_*})$$

I. Gas surface density



2. Dust height

B-fields

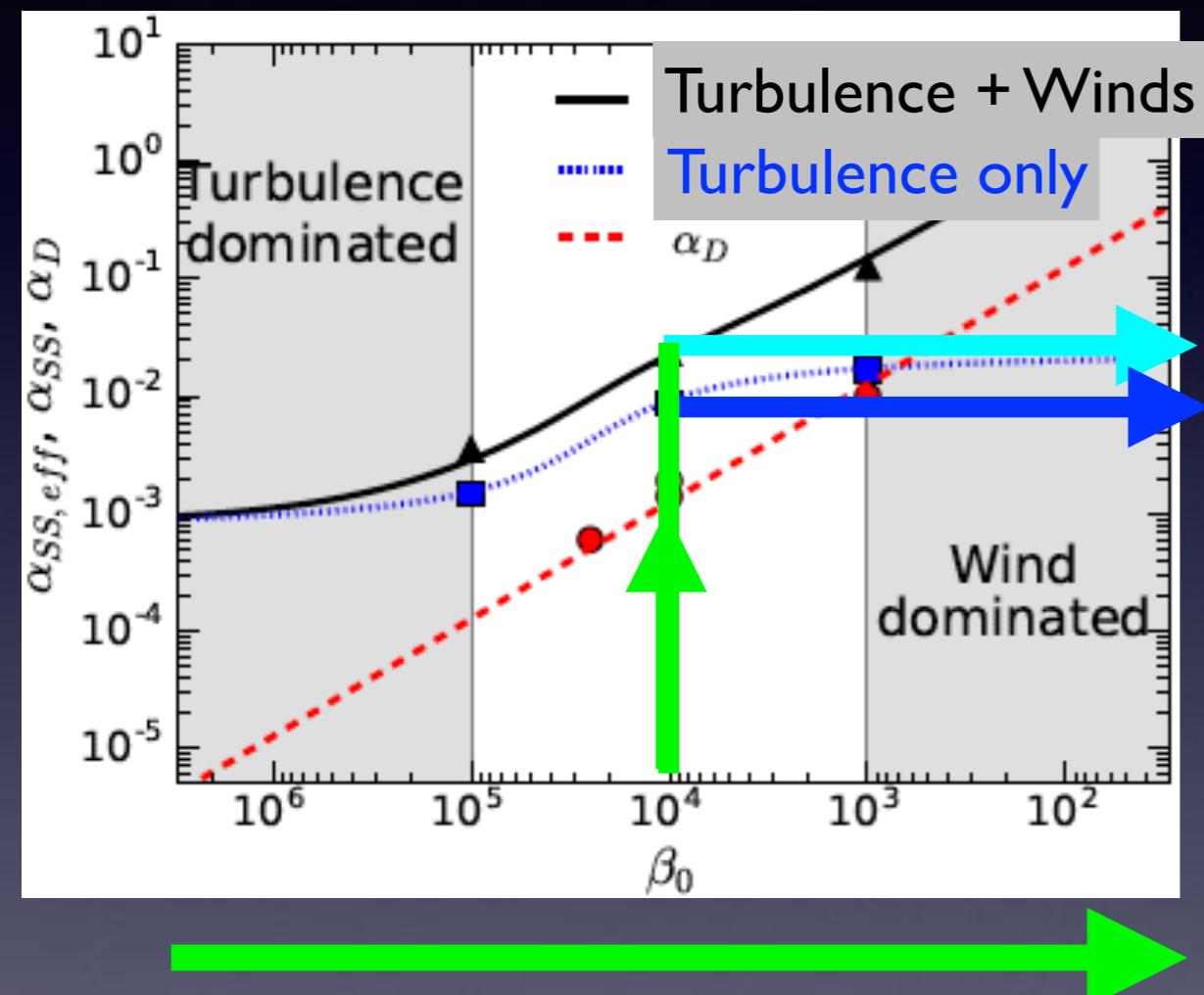
Given that

$$\dot{M}, c_s^2 (\propto T_d), \Omega (\propto \sqrt{M_*})$$

1. Gas surface density

$$\Sigma_g = \frac{\dot{M}\Omega}{3\pi\alpha_{GL}c_s^2}$$

2. Dust height



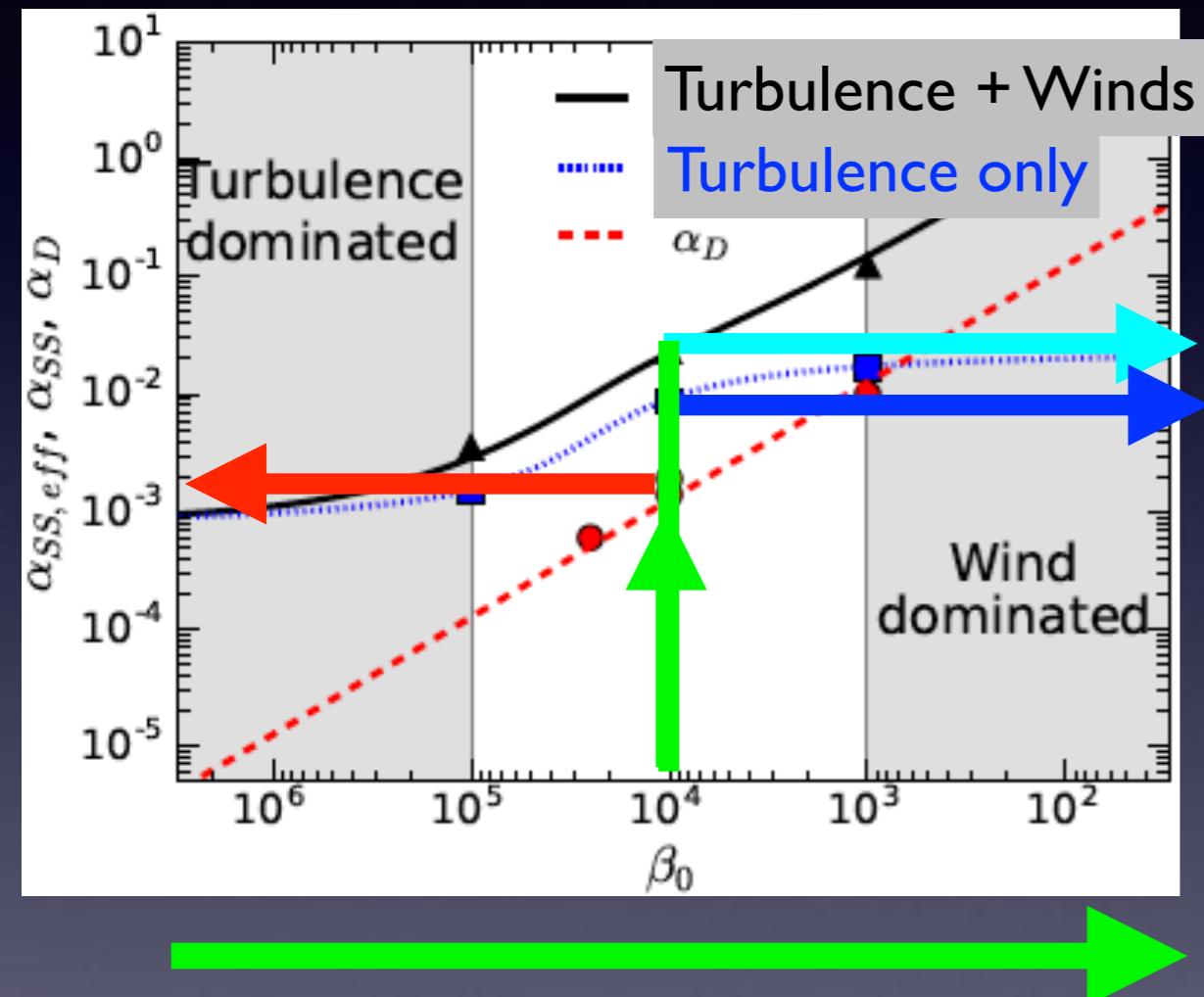
B-fields

Given that

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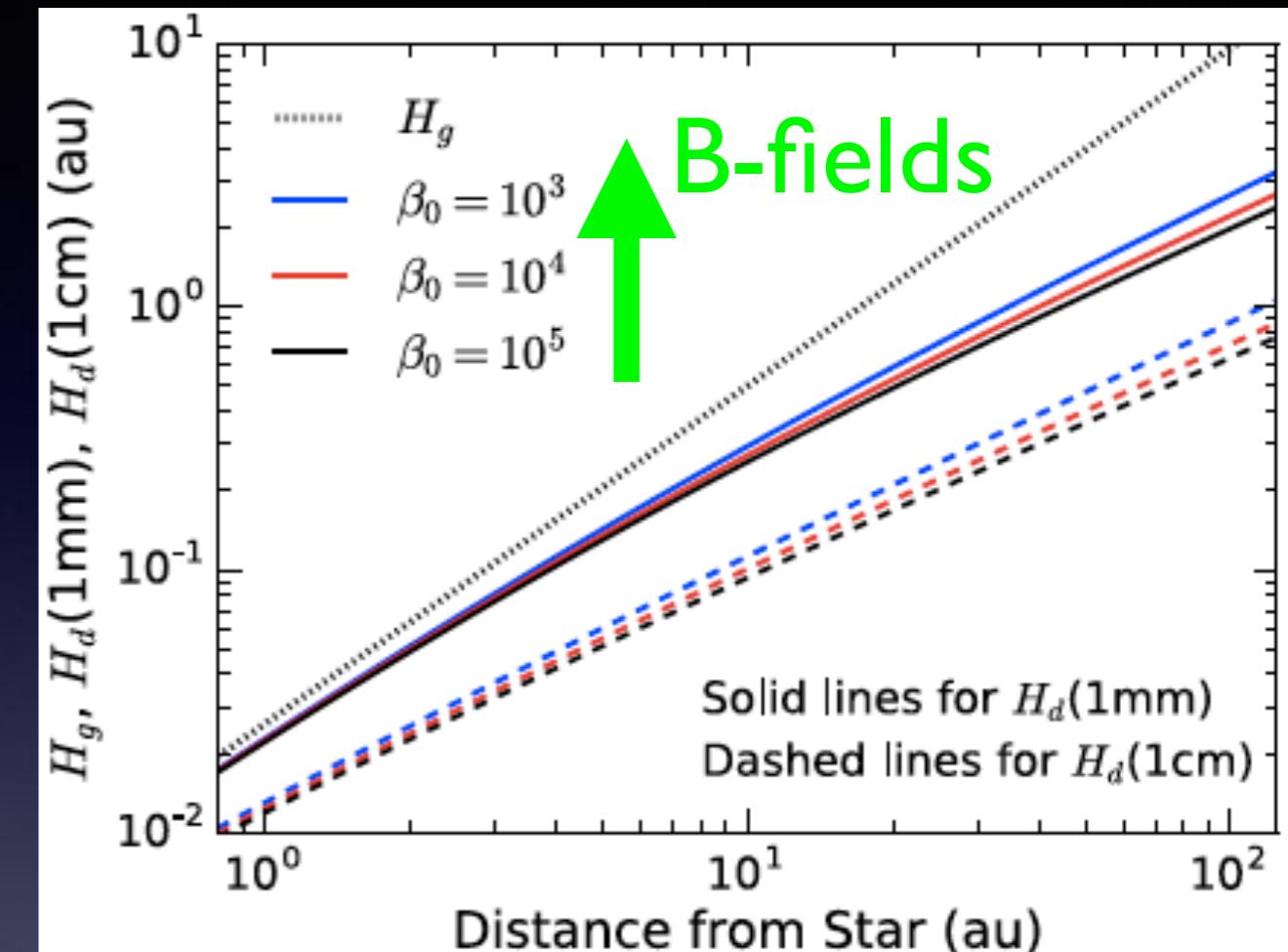
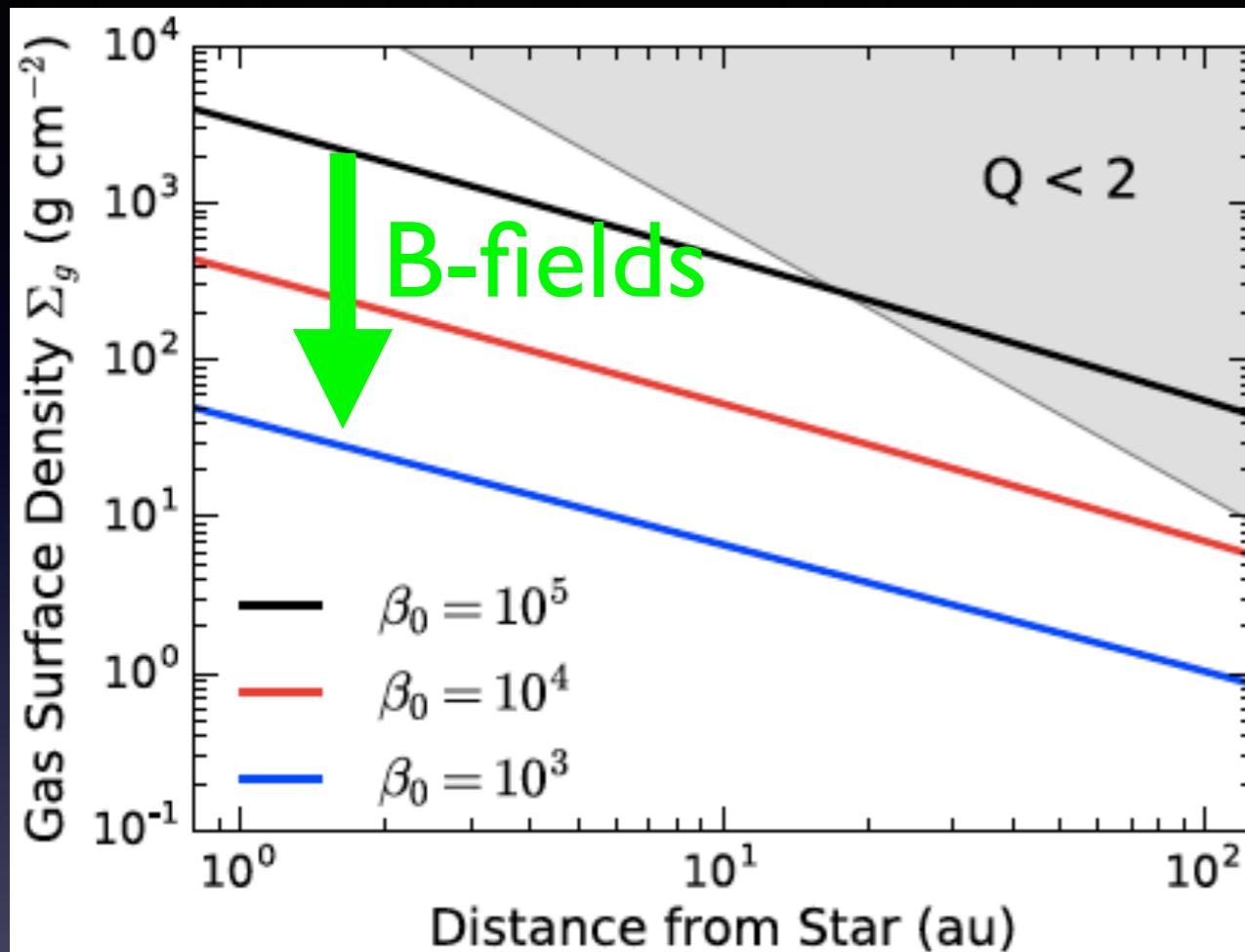
B-fields

2. Dust height

$$H_d = \left(1 + \frac{St}{\alpha_D} \right)^{-1/2} H_g$$

$$St \propto \frac{a}{\Sigma_g}$$

Ex) Resulting Disk Structures with Disk Winds

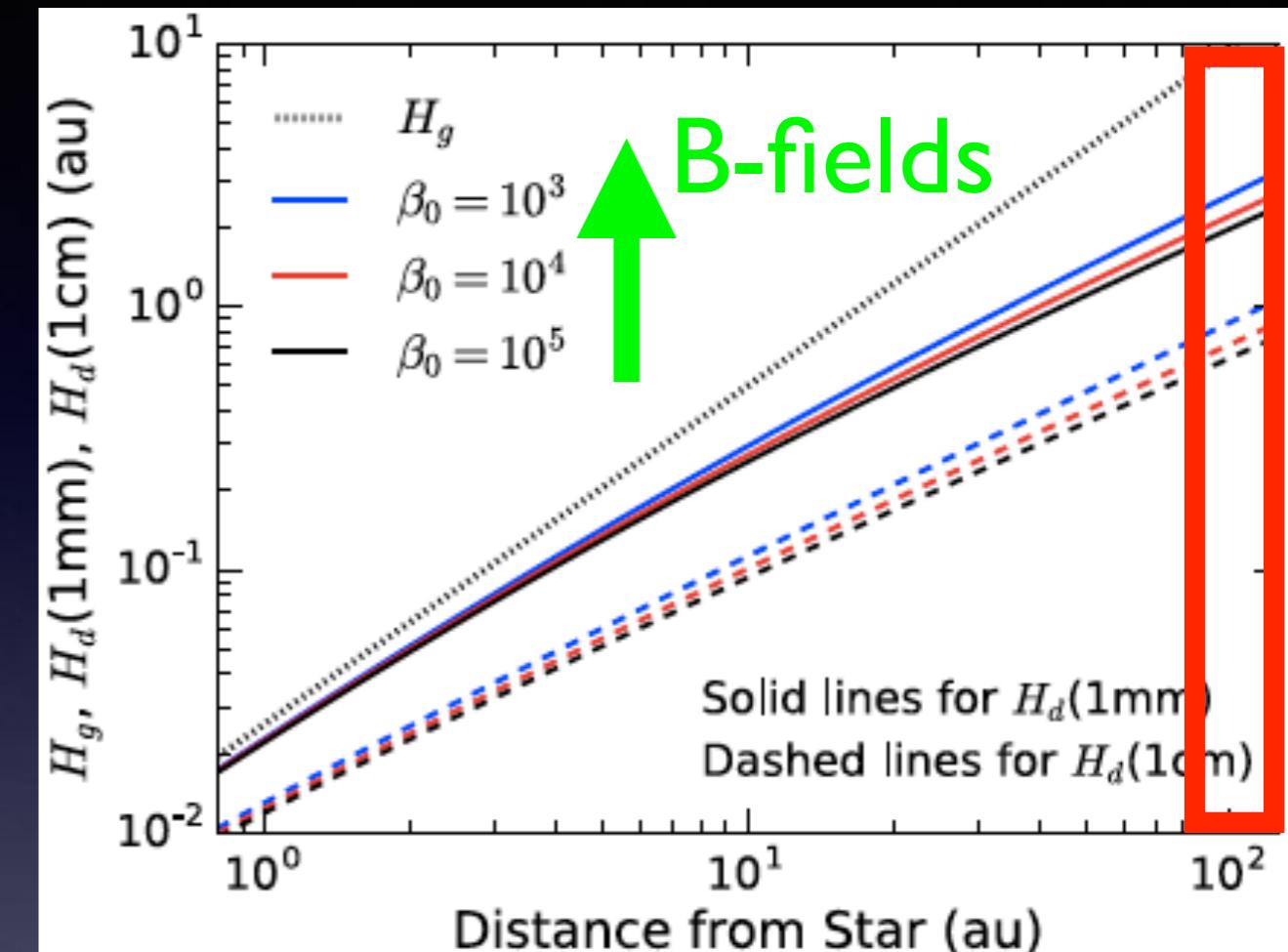
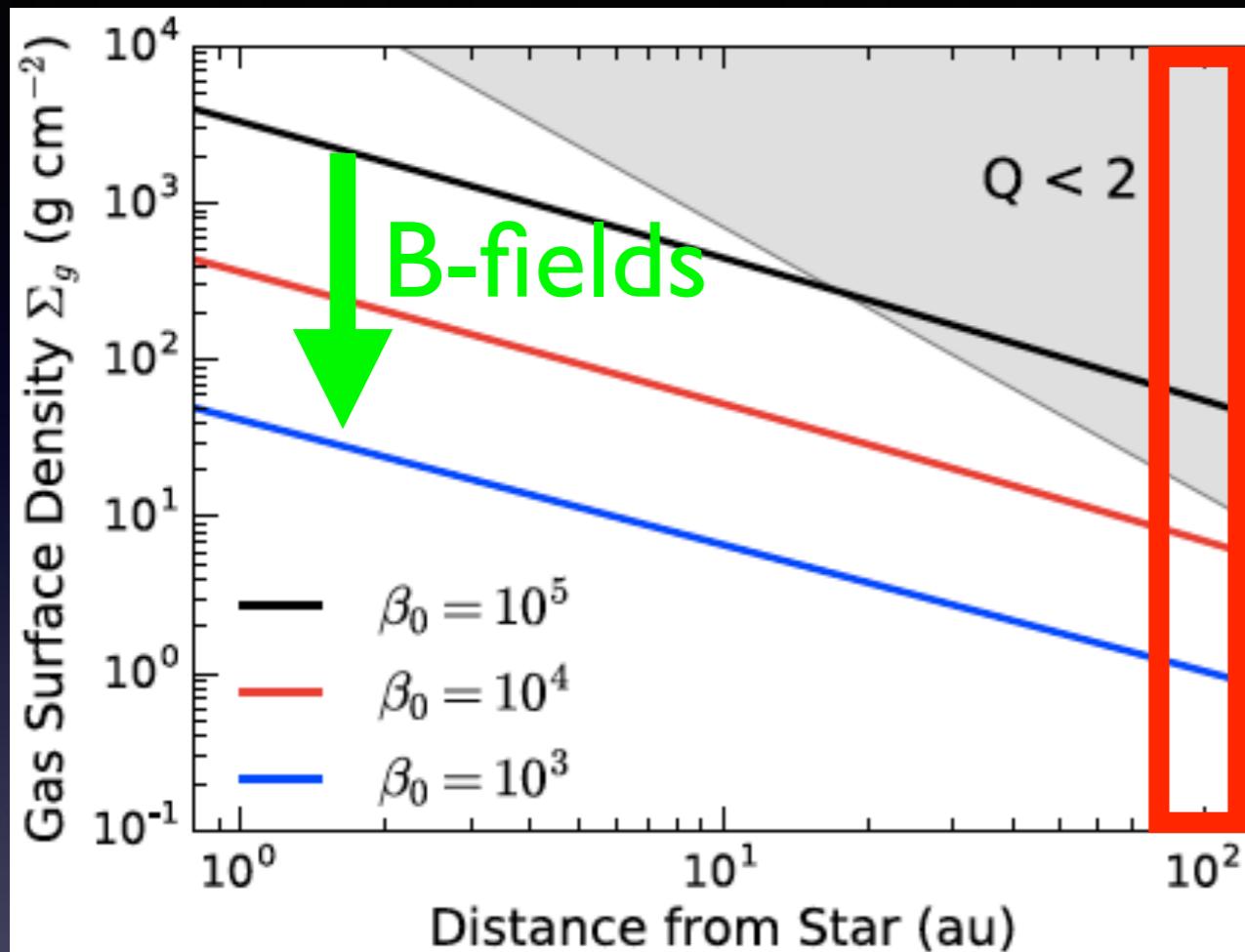


As B-fields are stronger,
surface density decreases
due to disk winds

Dust scale heights are
independent of B-fields

Results are obtained for given values of disk accretion rate, disk temperature

Ex) Resulting Disk Structures with Disk Winds



Focus on the HL Tau disk

Inversely solve the problem

I. Find β_0 with which Σ_g marginally avoids GI

II. Find β_0 with which the dust size satisfies $H_d = 1$ au

Results at $r = 100$ au

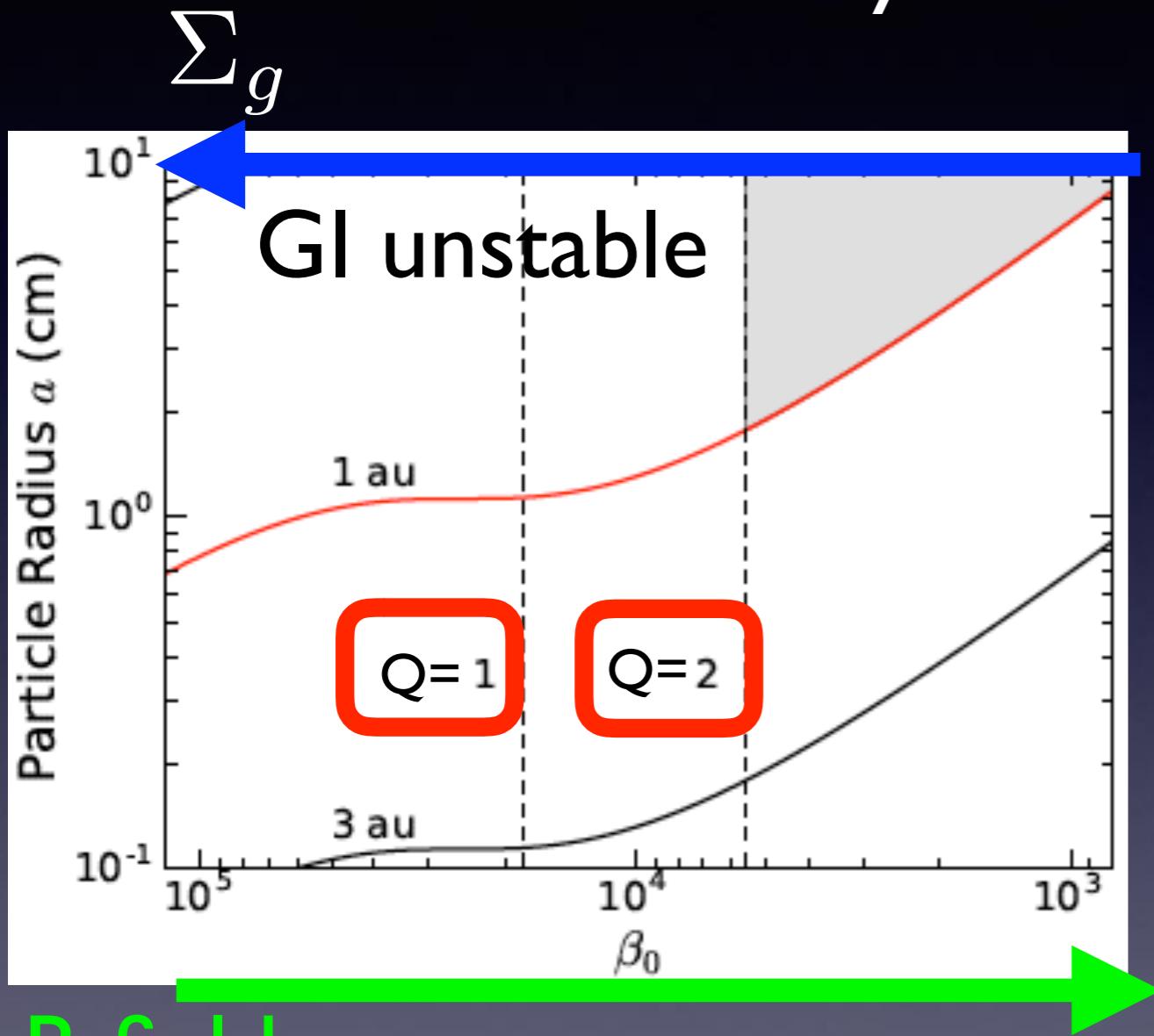
Turbulence only

Turbulence + Winds

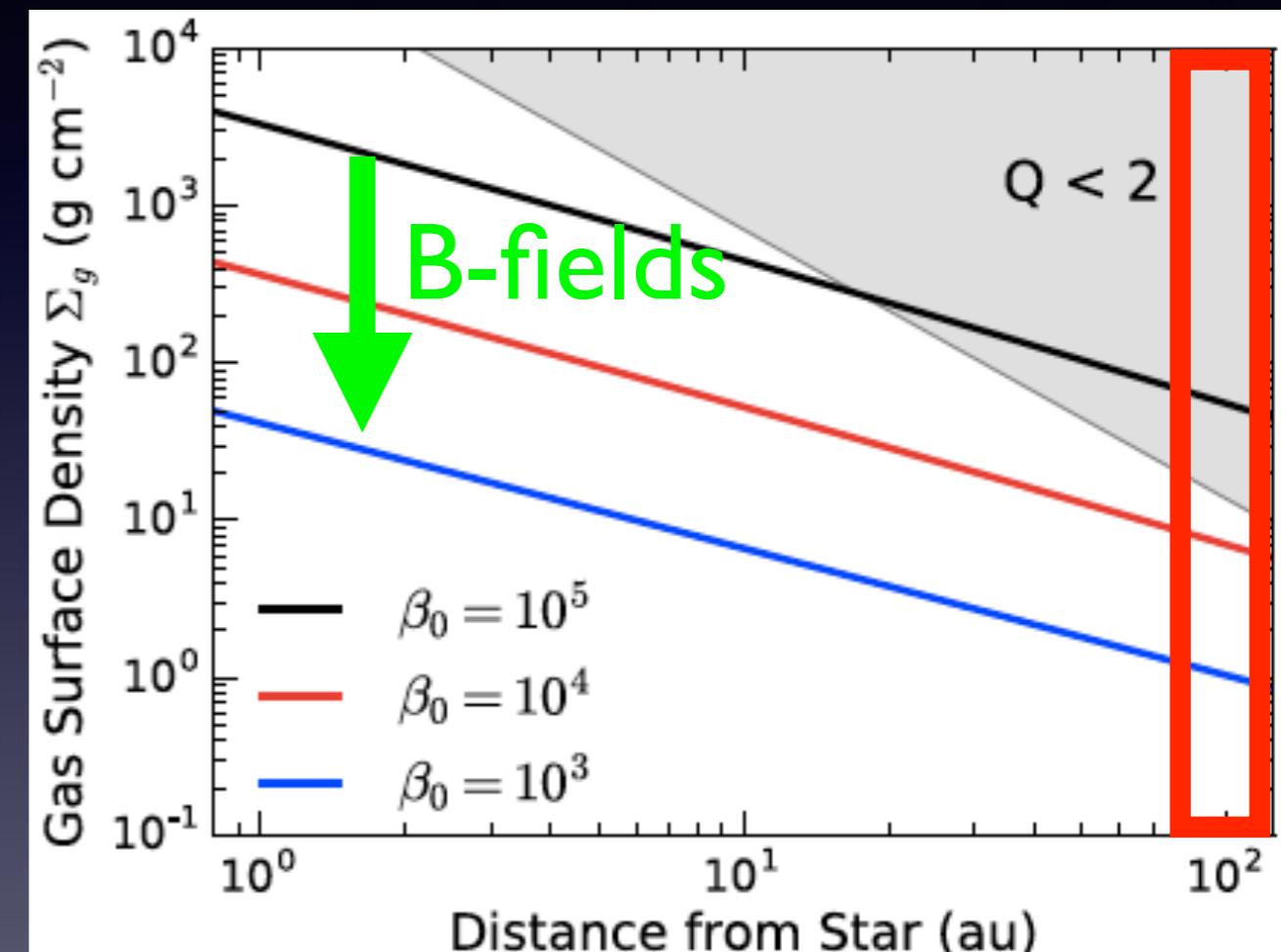
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Results at $r = 100$ au

Turbulence only



Turbulence + Winds

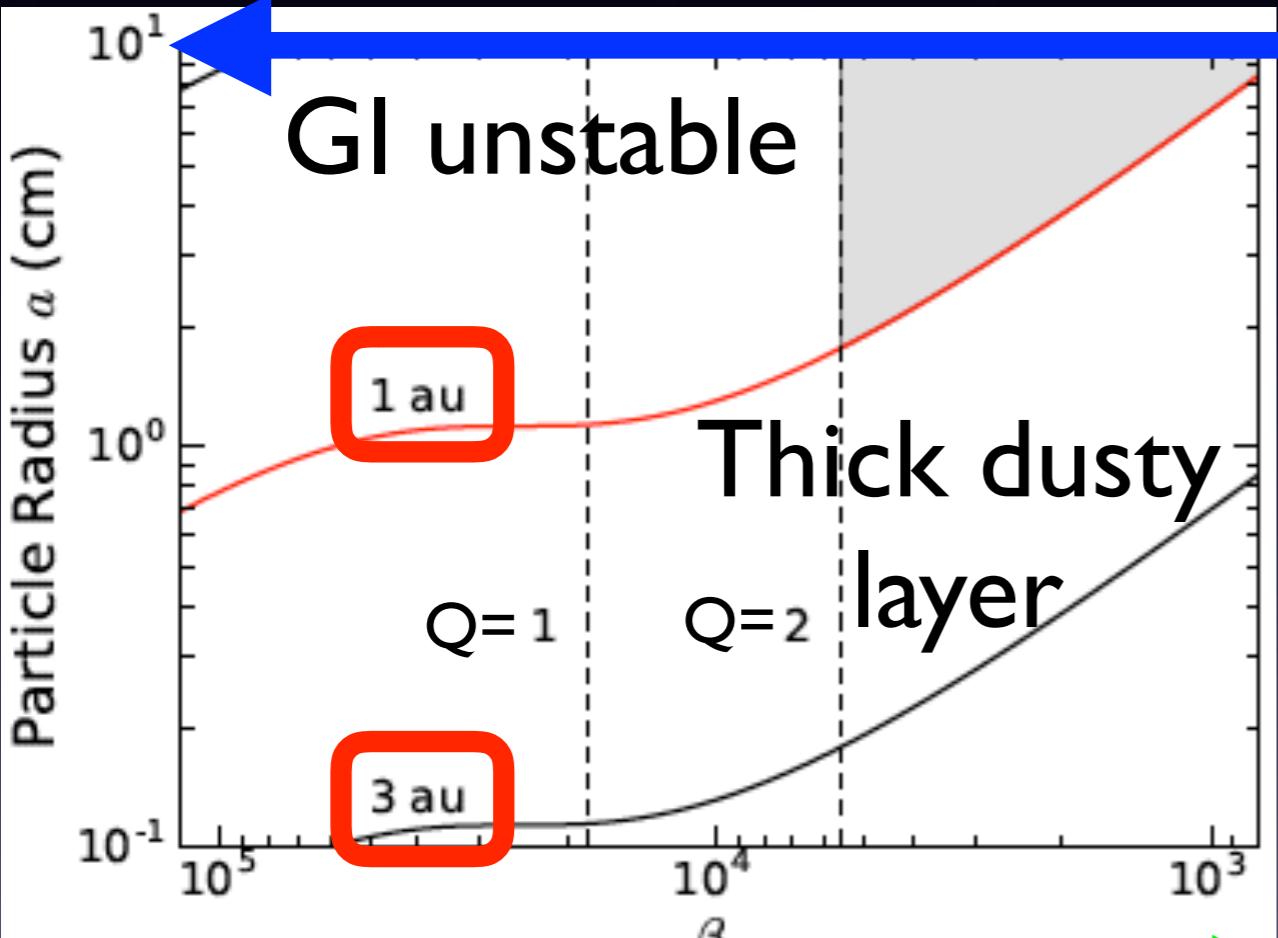


Results are obtained for given values of disk accretion rate, disk temperature

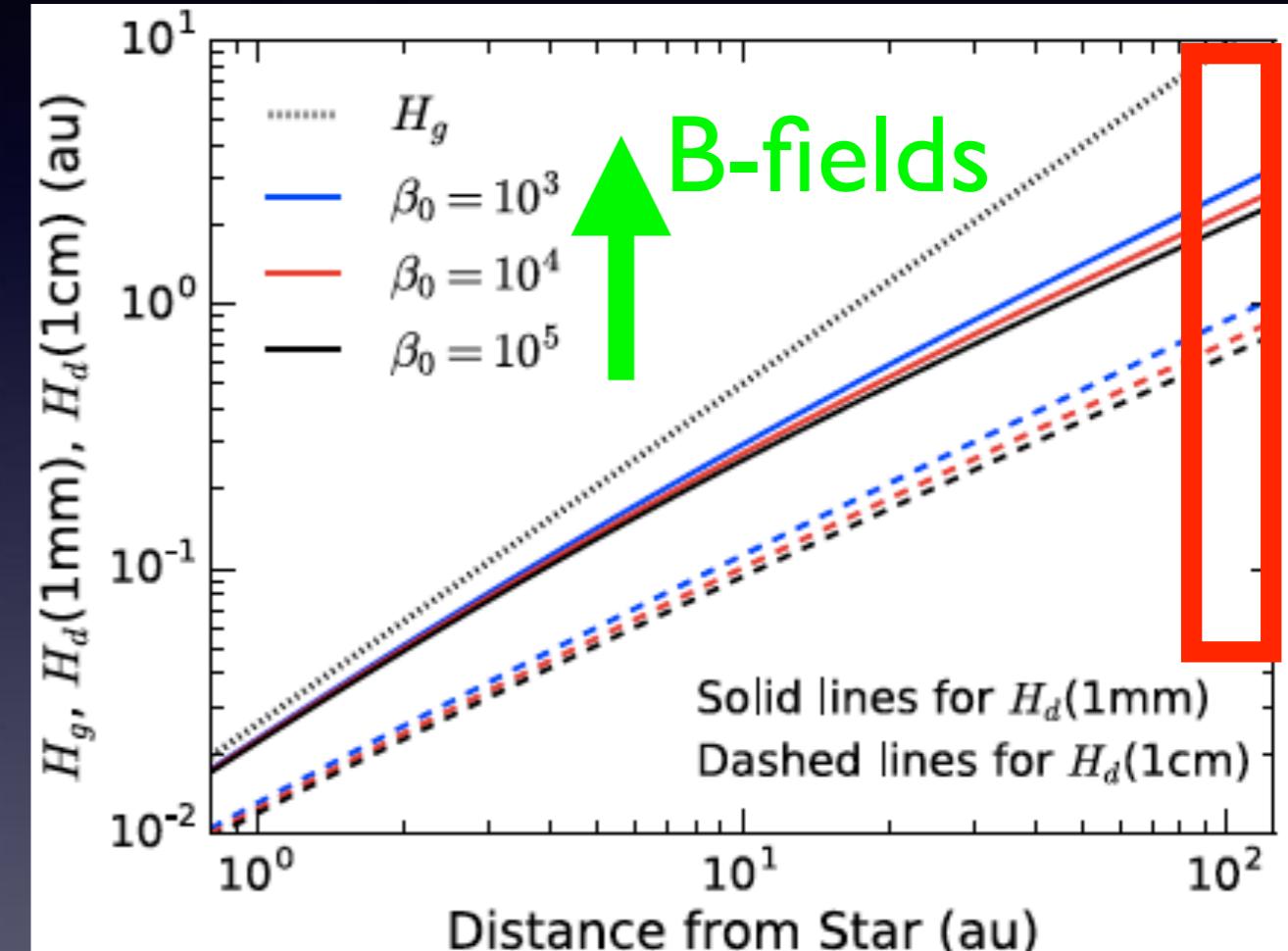
Results at $r = 100$ au

Turbulence only

$$\Sigma_g$$



Turbulence + Winds



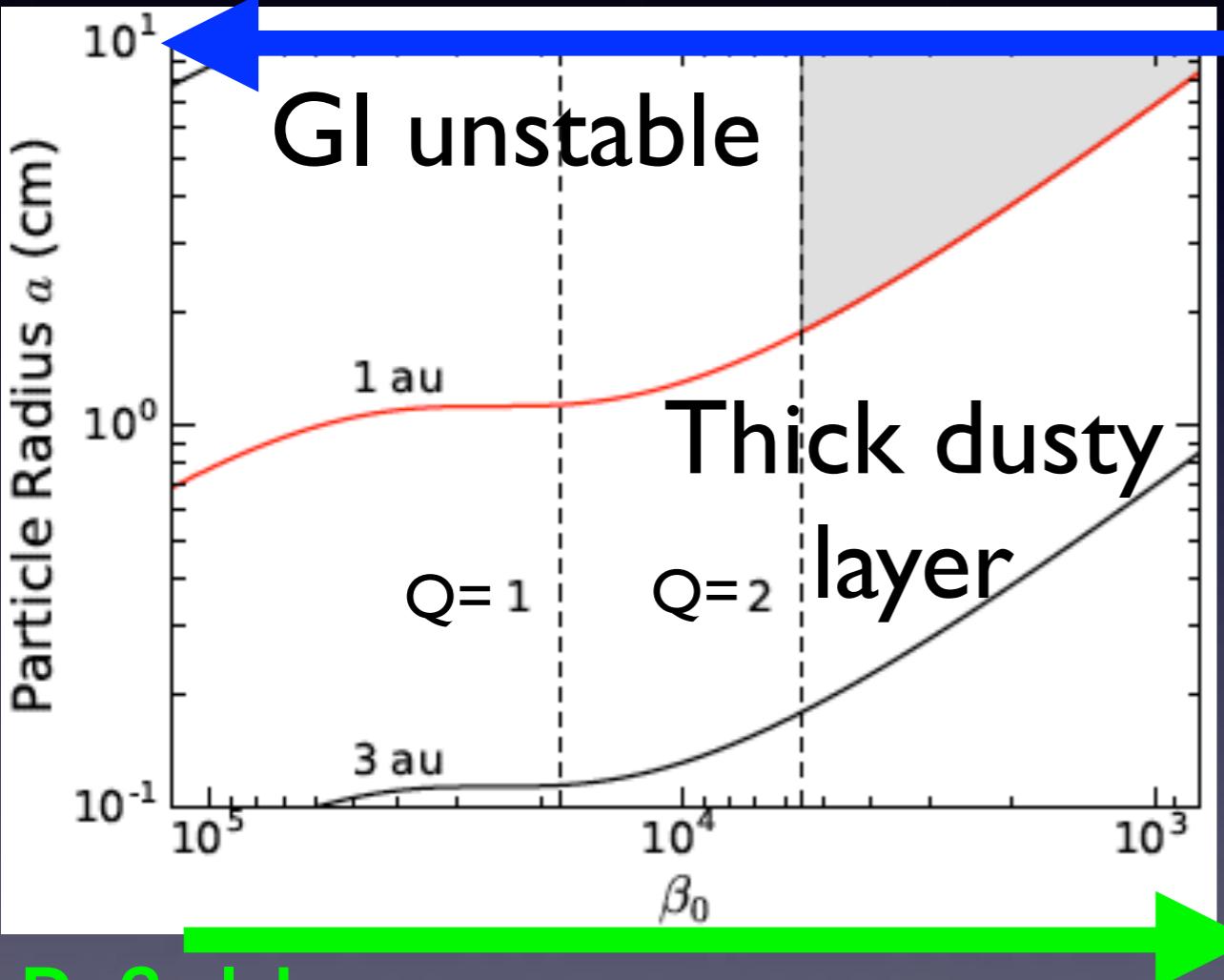
B-fields

Results are obtained for given values of disk accretion rate, disk temperature

Results at $r = 100$ au

Turbulence only

$$\Sigma_g$$

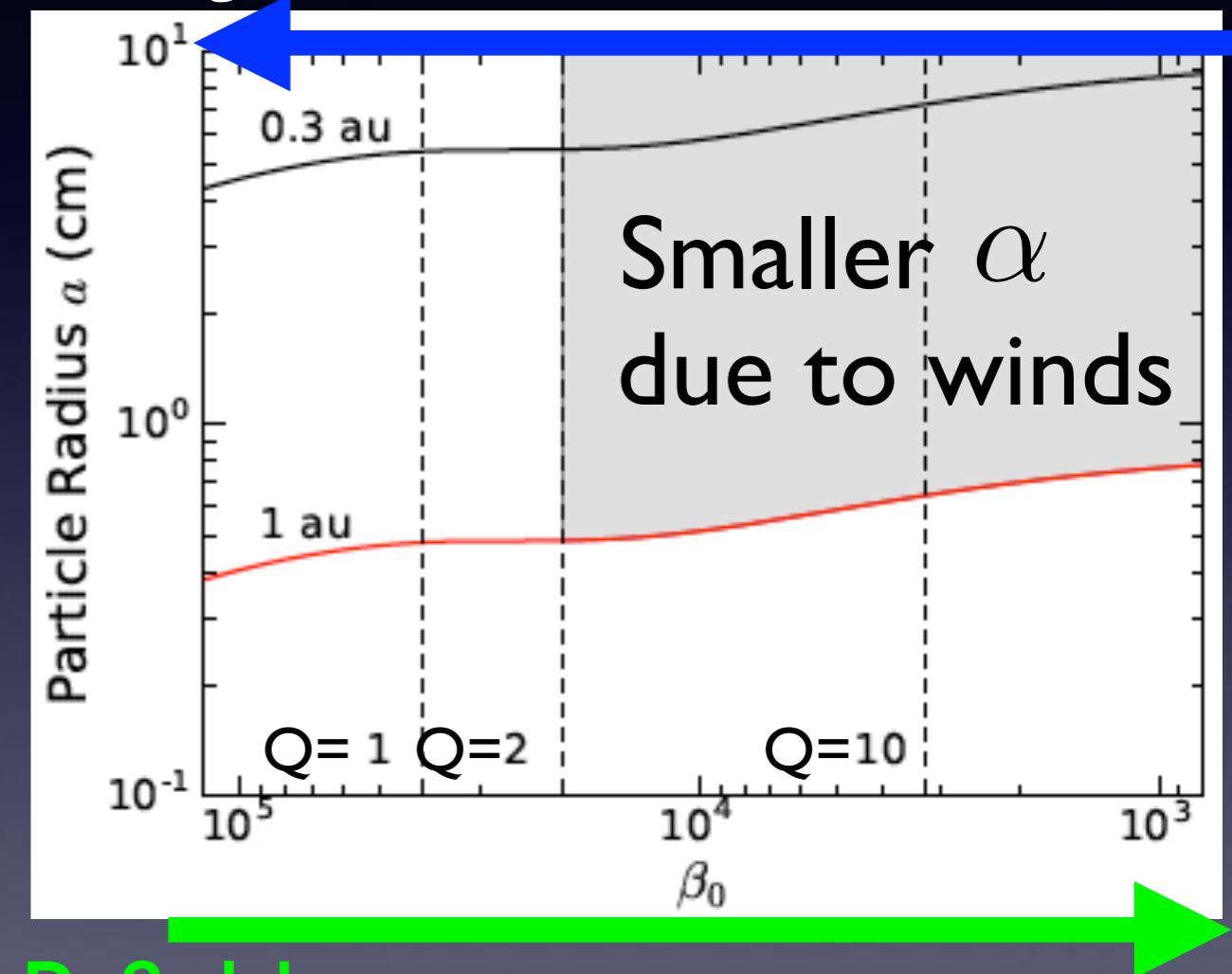


B-fields

20 mm-sized dust is needed
to reproduce ALMA image

Turbulence + Winds

$$\Sigma_g$$

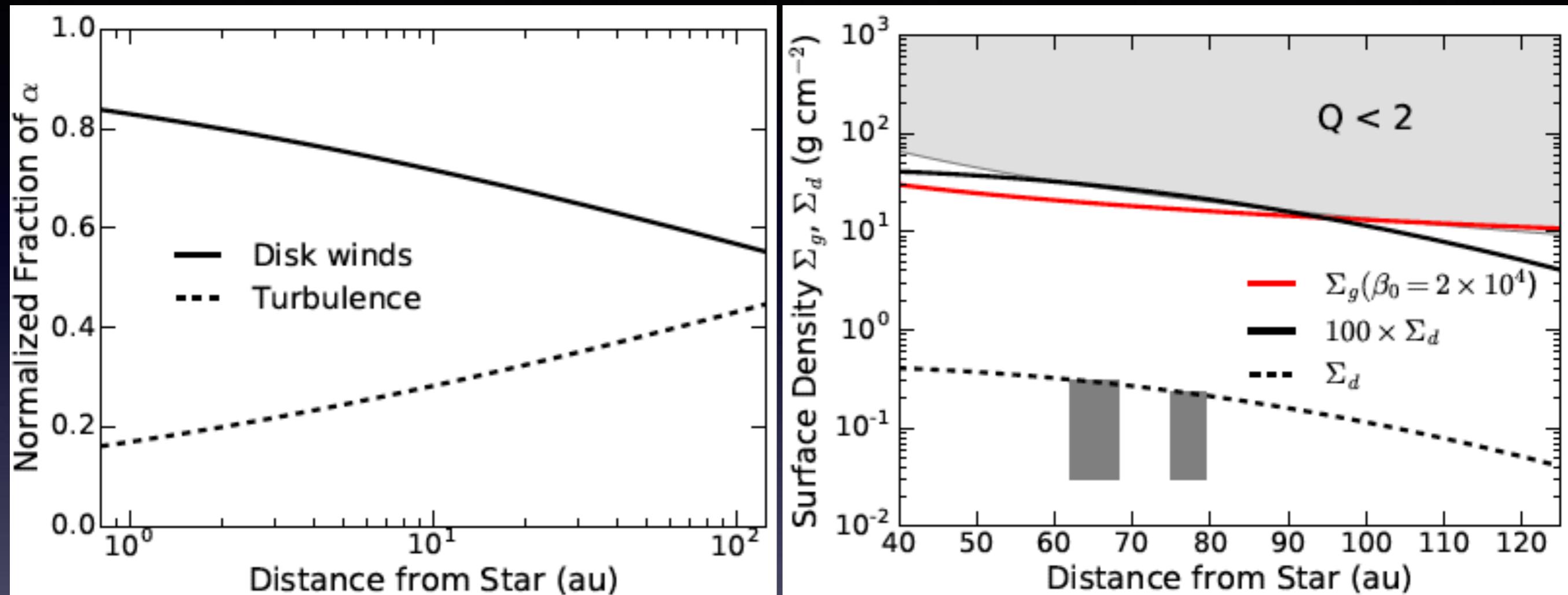


B-fields

4 mm-sized dust is needed
to reproduce ALMA image

Results are obtained for given values of disk accretion rate, disk temperature

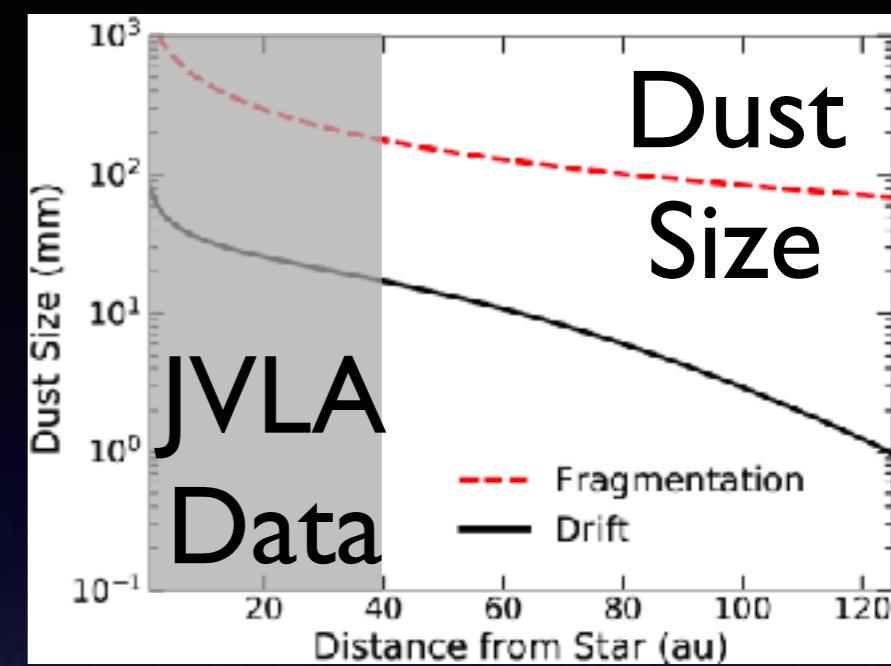
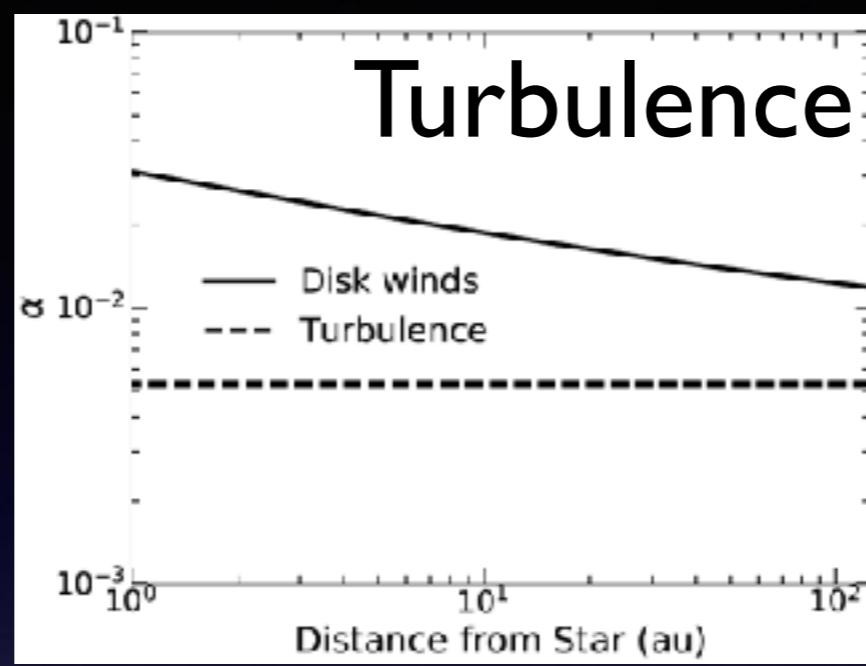
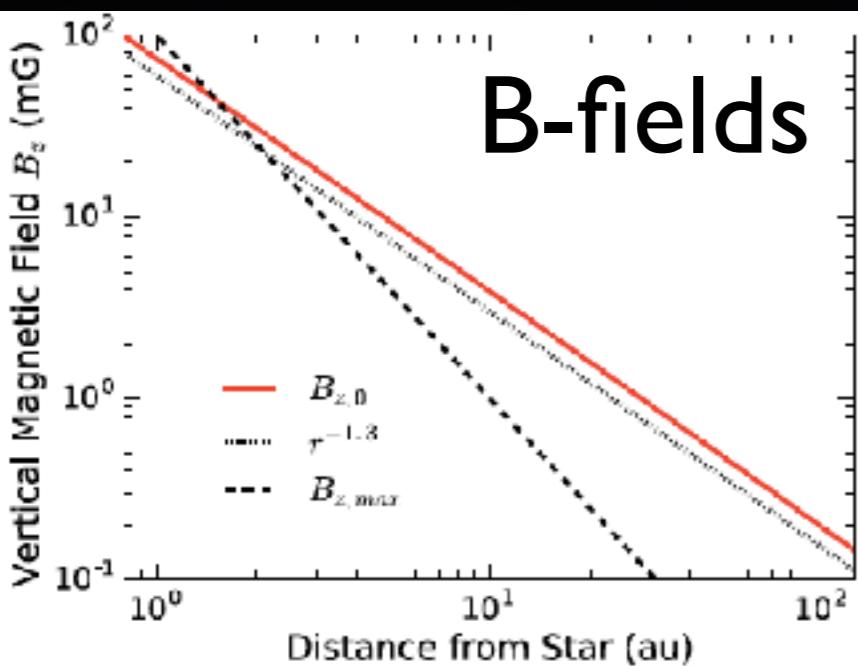
Resulting Global Structure of the HL Tau Disk



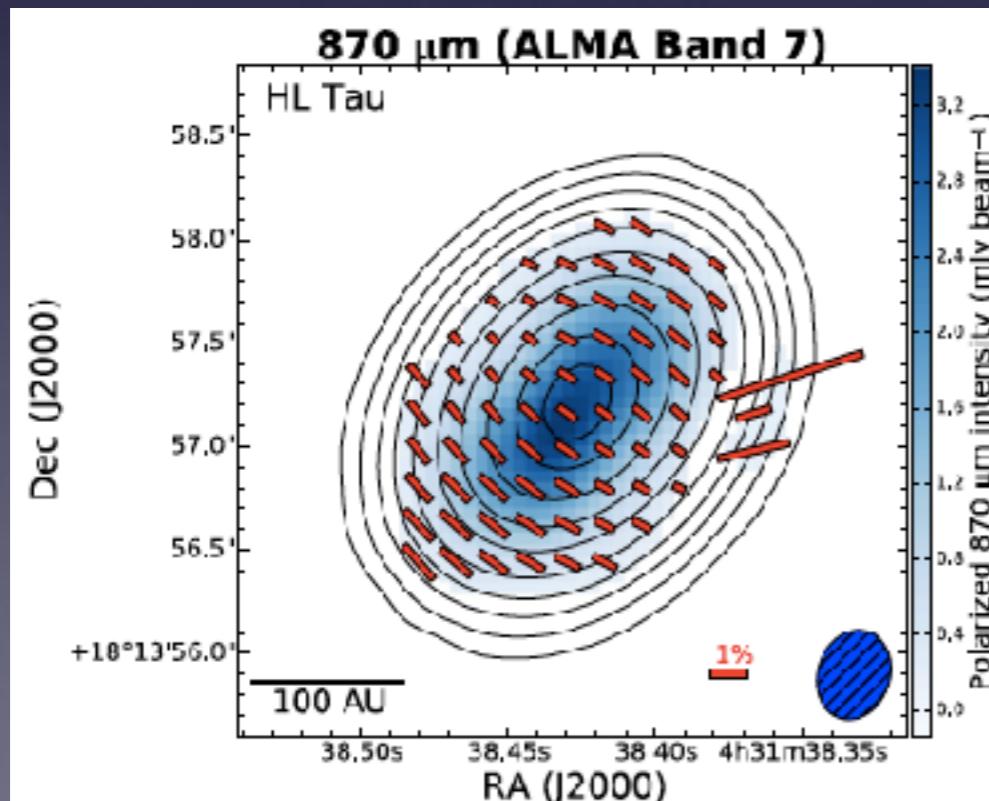
Disk winds transport the most of angular momentum (50-80 %) across the entire region of the disk

The gas-to-dust rate varies along the distance from the star (lower in the inner region & higher in the outer region)

Next Step

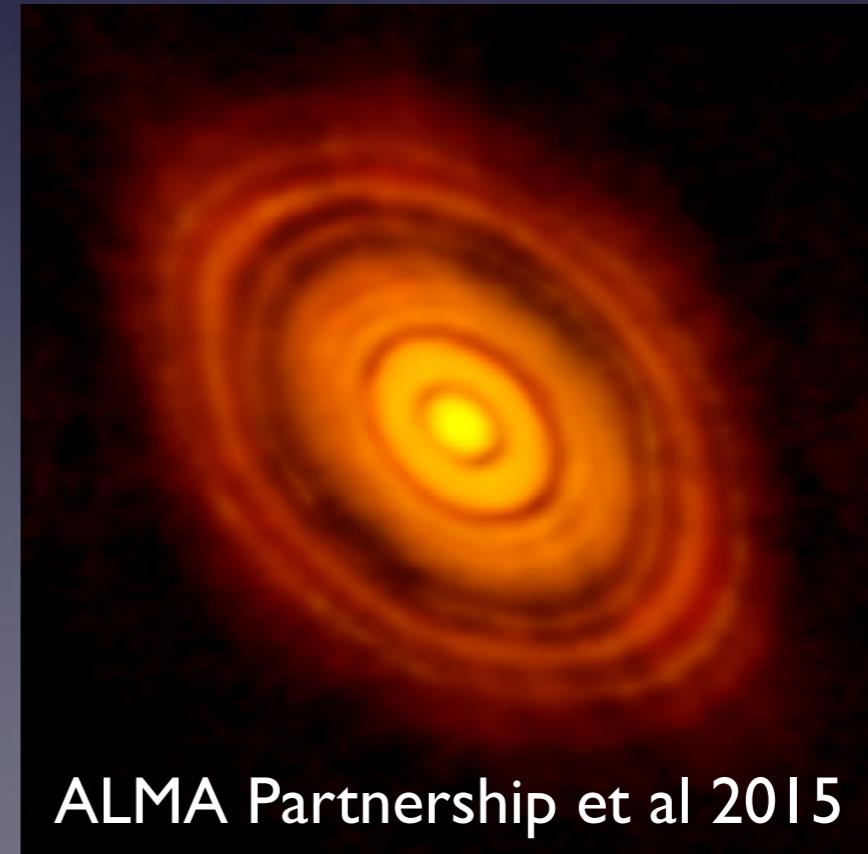


Polarization



Kataoka et al 2017, Stephens et al 2017

Origin of dust gaps



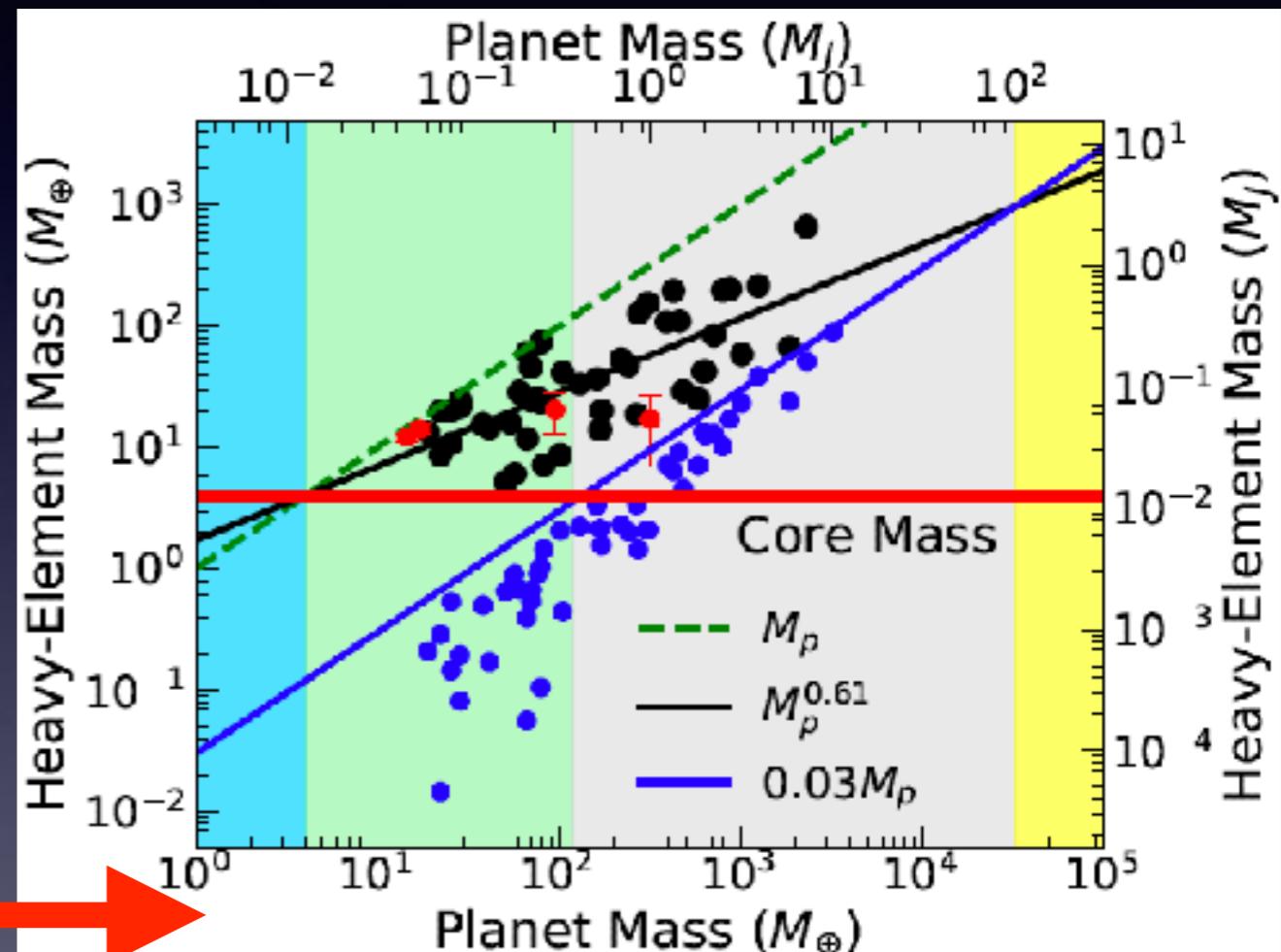
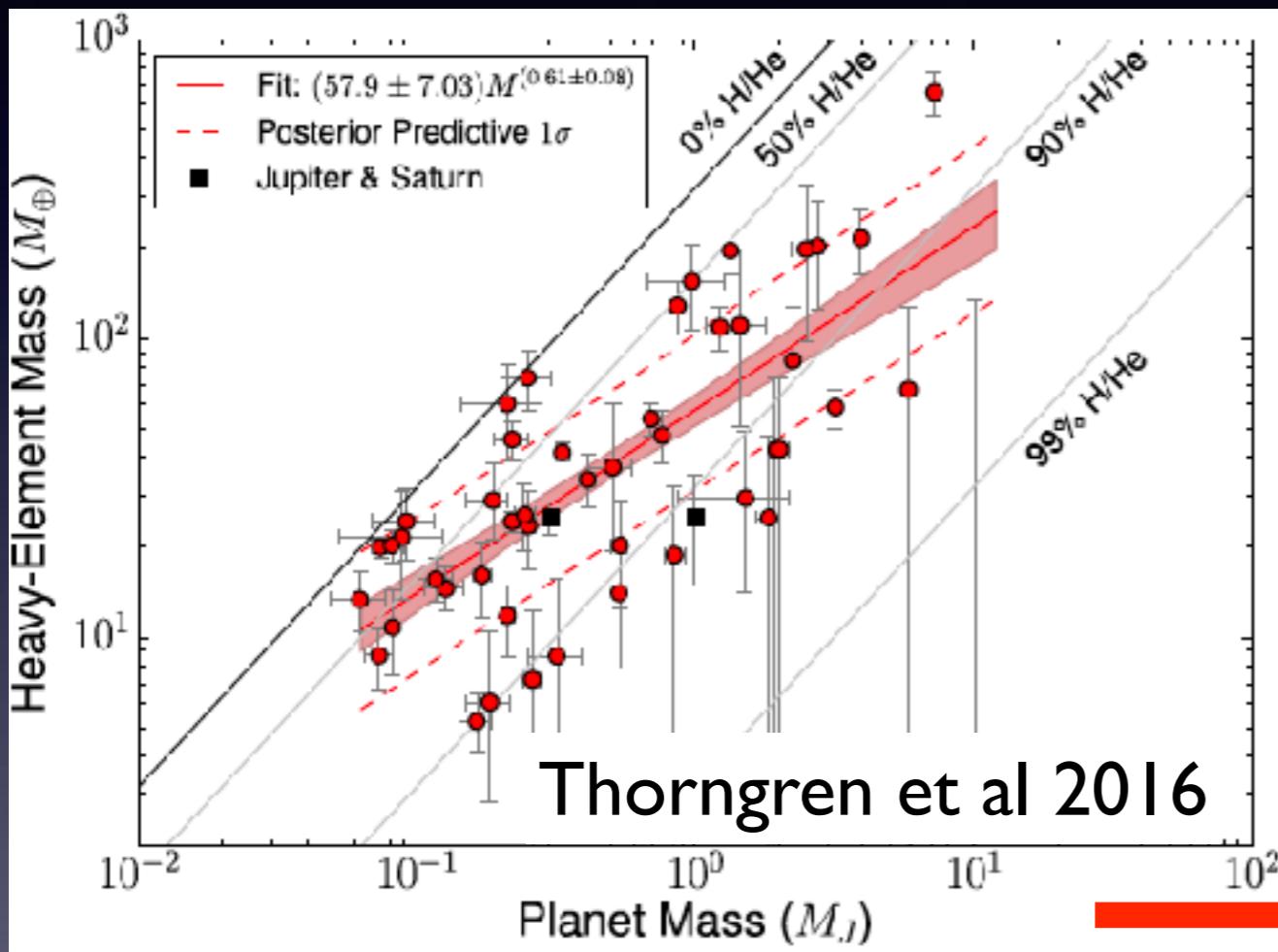
ALMA Partnership et al 2015
also see Akiyama et al 2016

Summary

Hasegawa et al 2017,ApJ, 845, 31

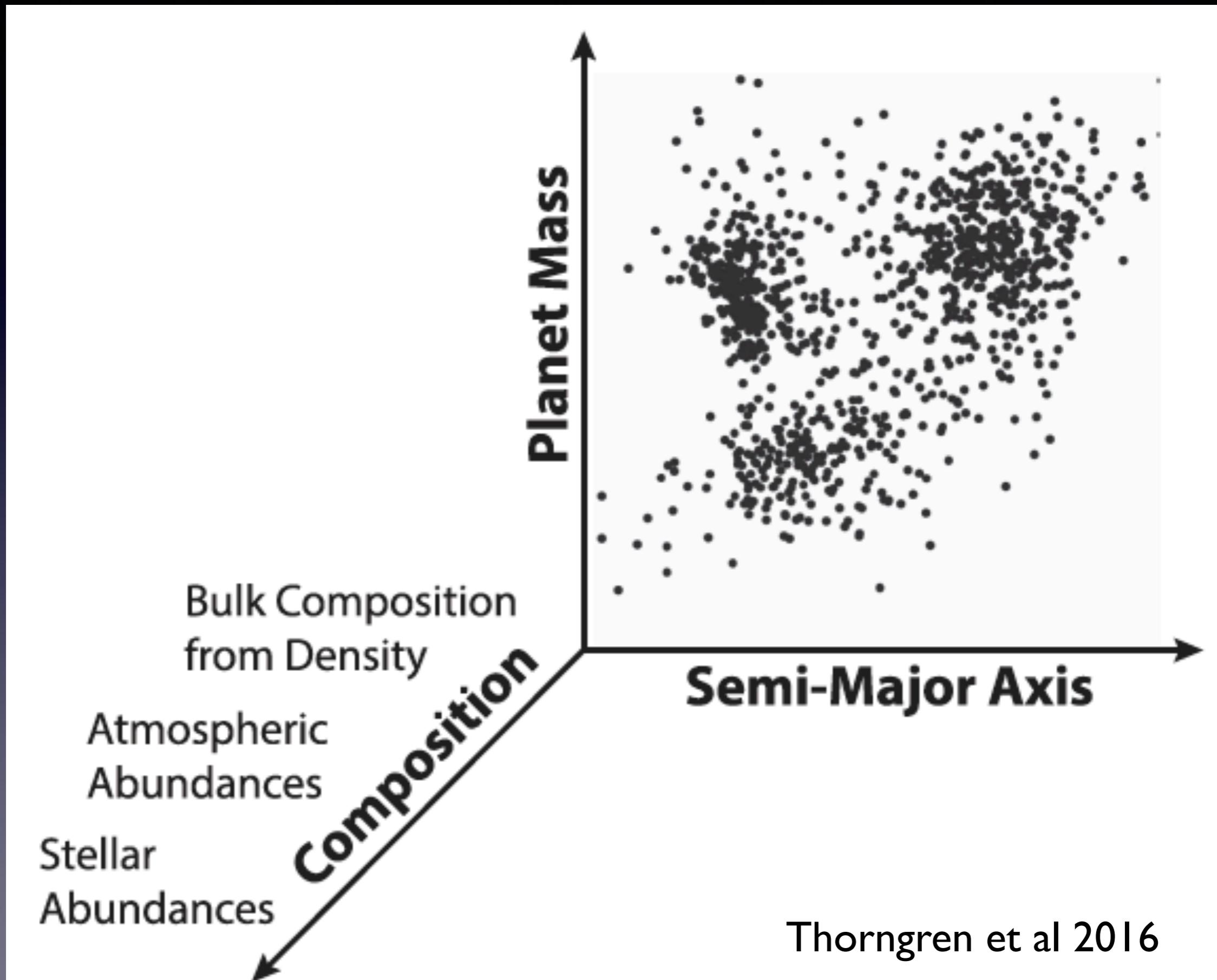
- ALMA observations of the HL Tau disk can advance our understanding of **disk evolution**
- Subsequent radiative transfer modeling suggests a higher degree of dust settling for the actively accreting disk
- Developed the simple, semi-analytical model, taking into account magnetically induced disk winds
- Our results indicate the importance of **magnetically induced disk winds** to fully reproduce the global configuration
- Followup work will be performed to obtain a better understanding of **polarization** observations and to identify the origins of observed **multiple gaps** in the HL Tau disk

The Origin of the Heavy Element Content Trend in Giant Planets



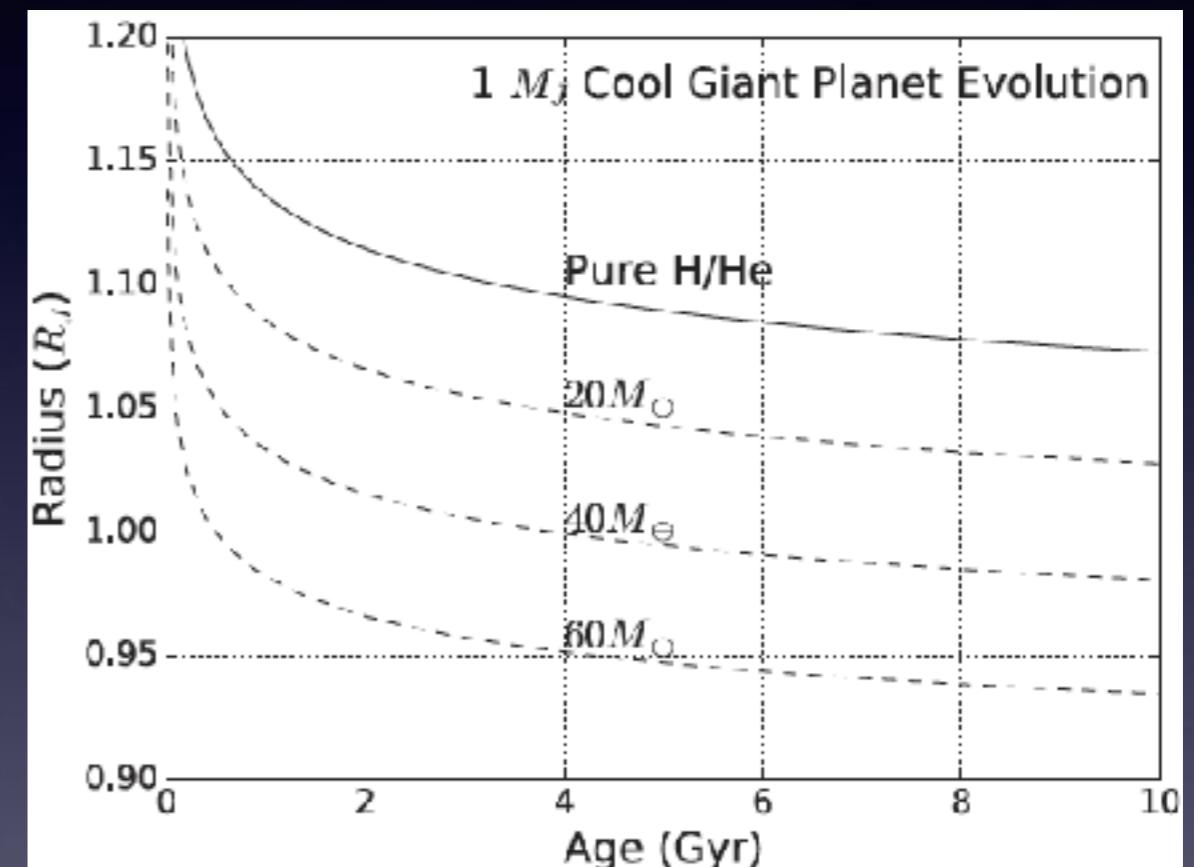
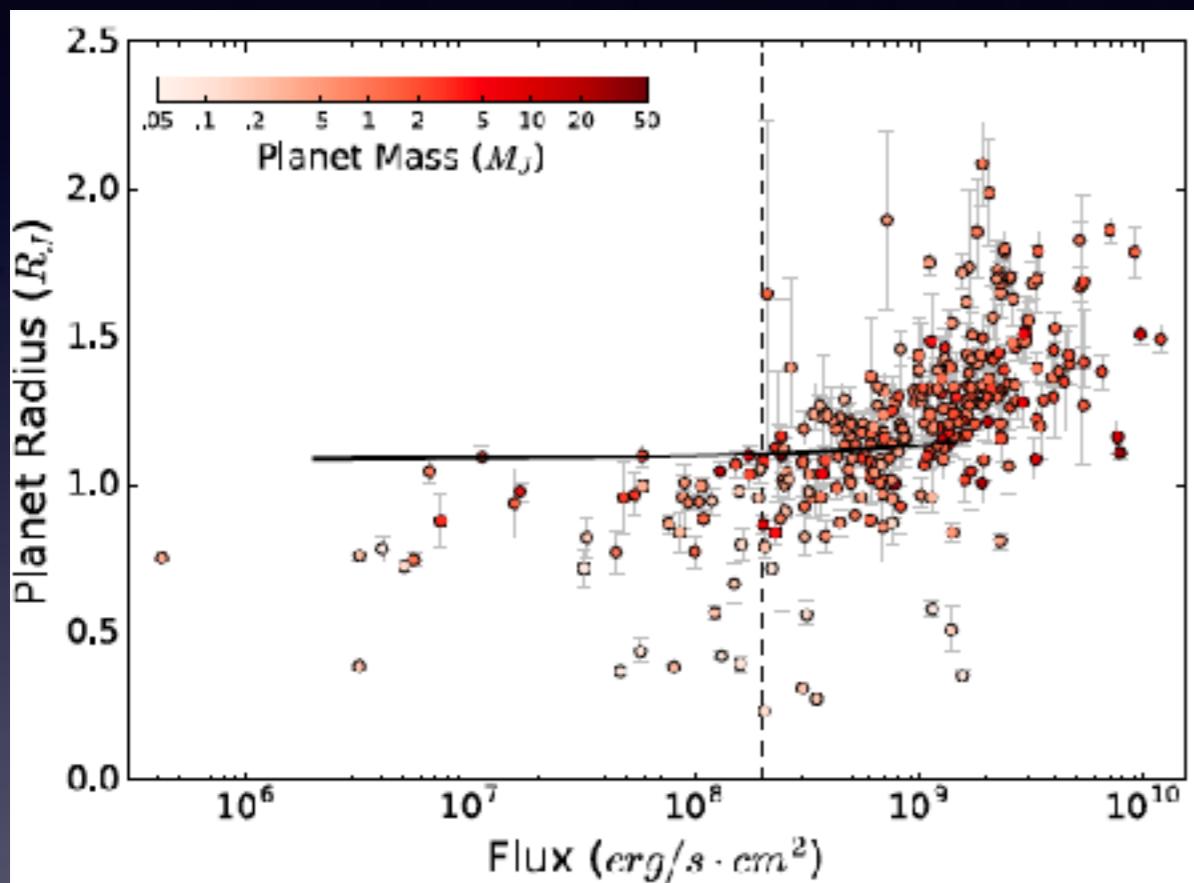
in collaboration with
Geoff Bryden, Masahiro Ikoma, Gautam Vasisht, Mark Swain

How do Planets form?



Estimate of the heavy element mass in observed exoplanets

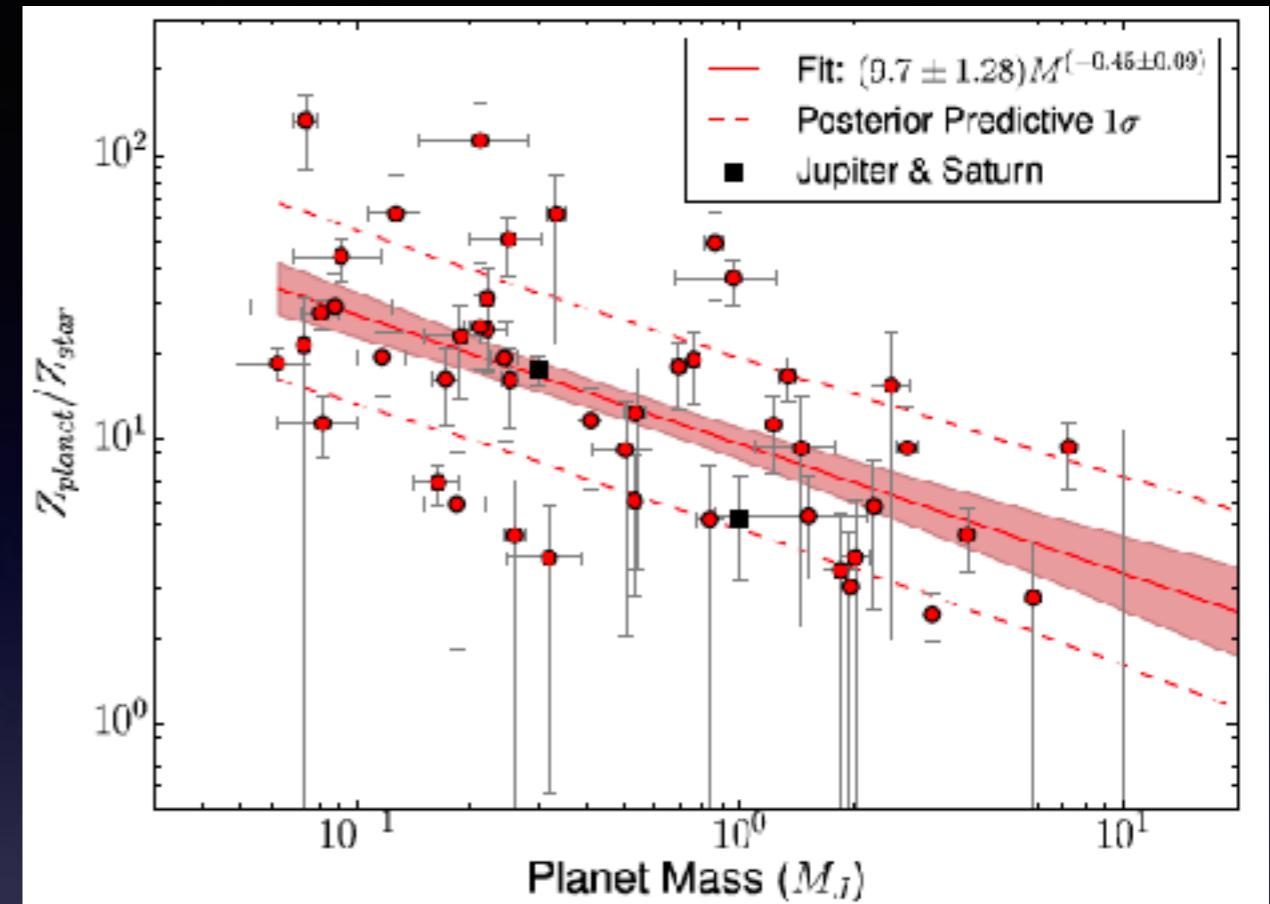
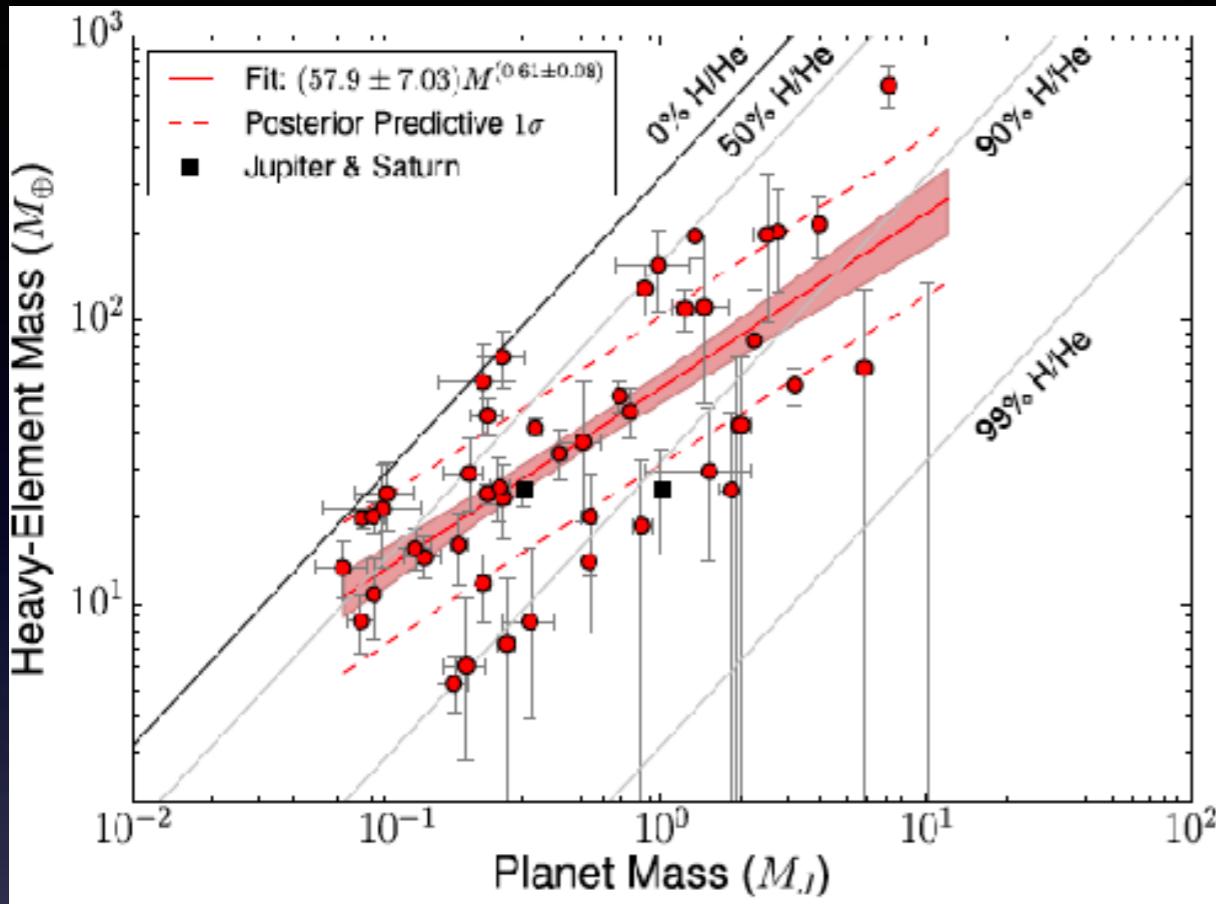
e.g., Guillot et al 2006; Miller & Fortney 2011; Thorngren et al 2016



Target selection: relatively cool close-in exoplanets

Distribute heavy elements in cores and envelopes,
and compute the radius evolution of planets

Results of Thorngren et al 2016 (T16)



$$M_Z \propto M_p^{\Gamma} \text{ with } \Gamma = 0.61 \pm 0.08 \simeq 3/5$$

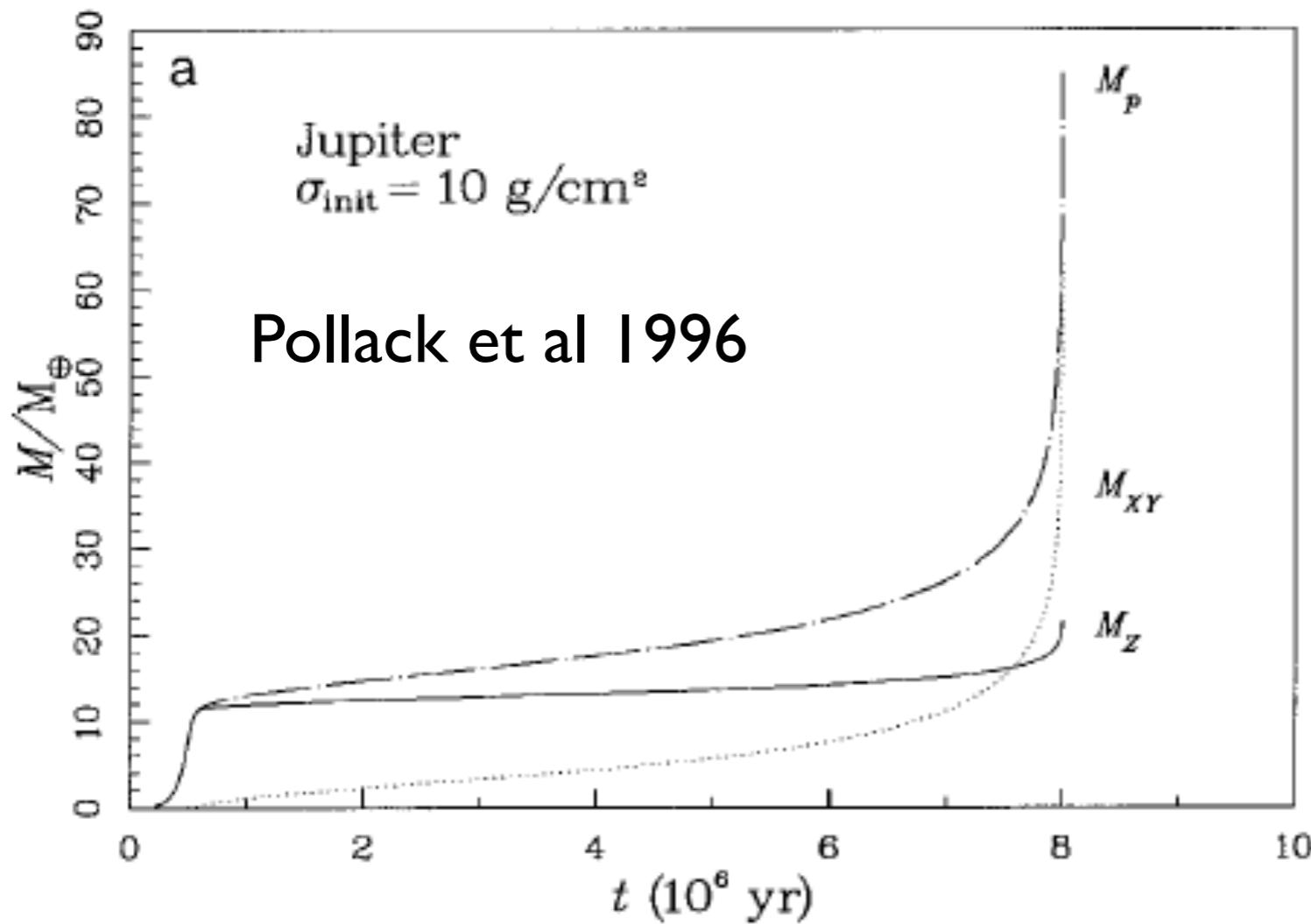
$$\frac{Z_p}{Z_s} = \frac{M_Z}{M_p Z_s} \propto M_p^{\beta} \text{ with } \beta = -0.45 \pm 0.09 \simeq -2/5$$

$\Gamma - 1 \simeq \beta \Rightarrow M_Z$ and M_p are almost independent of Z_s

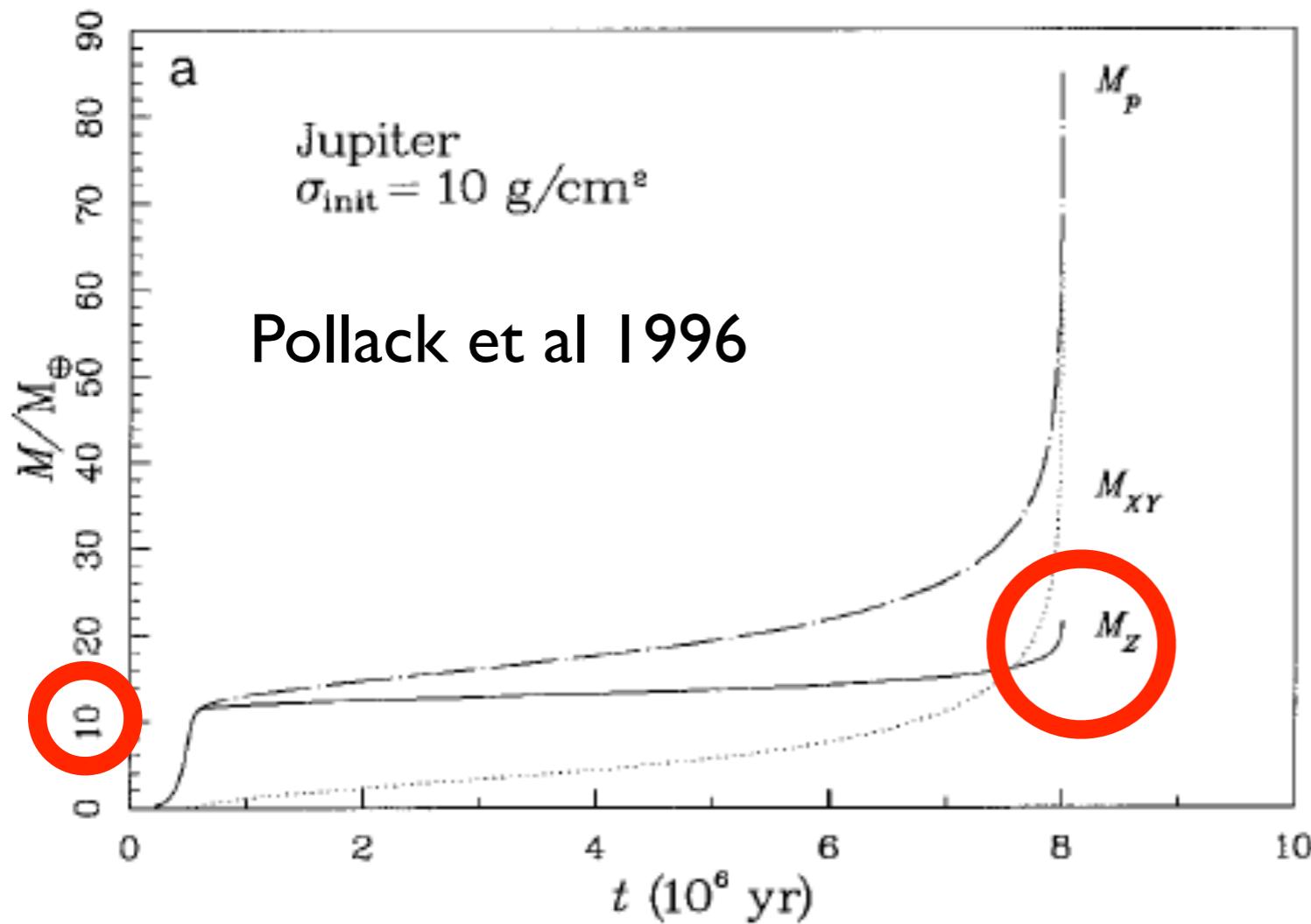
M_Z : the total heavy element mass in planets with the mass of M_p

Z_s : the metallicity of the host star

Planet Formation via Core Accretion: Accretion of Gas and Solids



Planet Formation via Core Accretion: Accretion of Gas and **Solids**

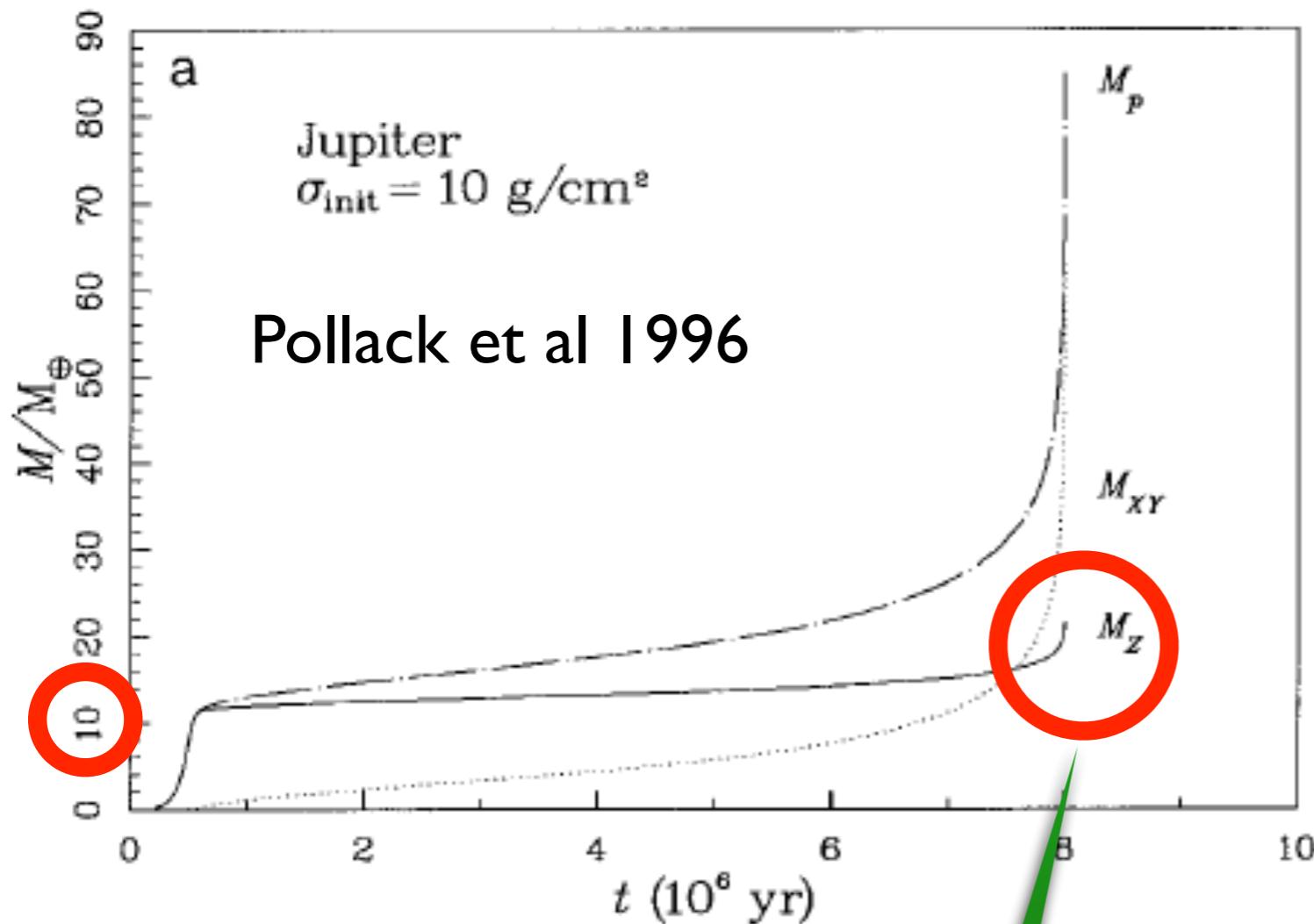


$$M_{\text{core}} \simeq 10M_\oplus$$

M_z increases at the final formation stage



Planet Formation via Core Accretion: Accretion of Gas and **Solids**



$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{\text{core}} + M_{\text{pl}} + M_{\text{pe}} + M_{Z,\text{gas}}$$

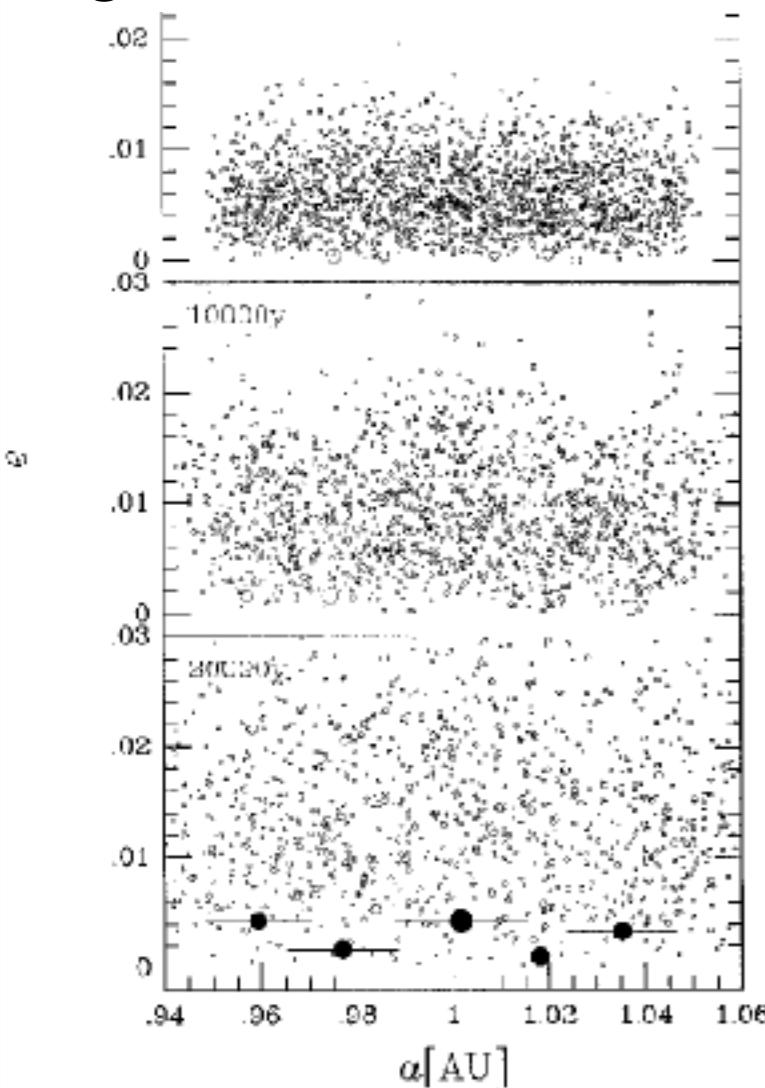
Planetsimals

Pebbles

dust in gas



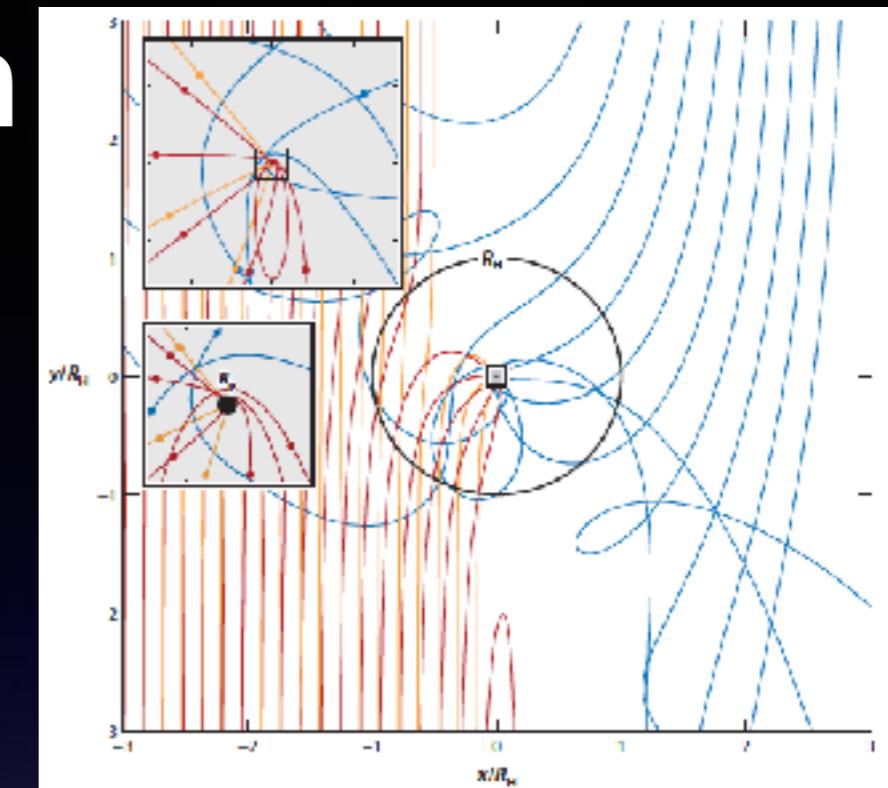
e.g., Kokubo & Ida 2000



Core formation

Oligarchic growth

Pebble accretion



e.g., Johansen & Lambrechts 2017

M_{core} :determined by disk properties
:independent of M_p

$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$

Planetsimals

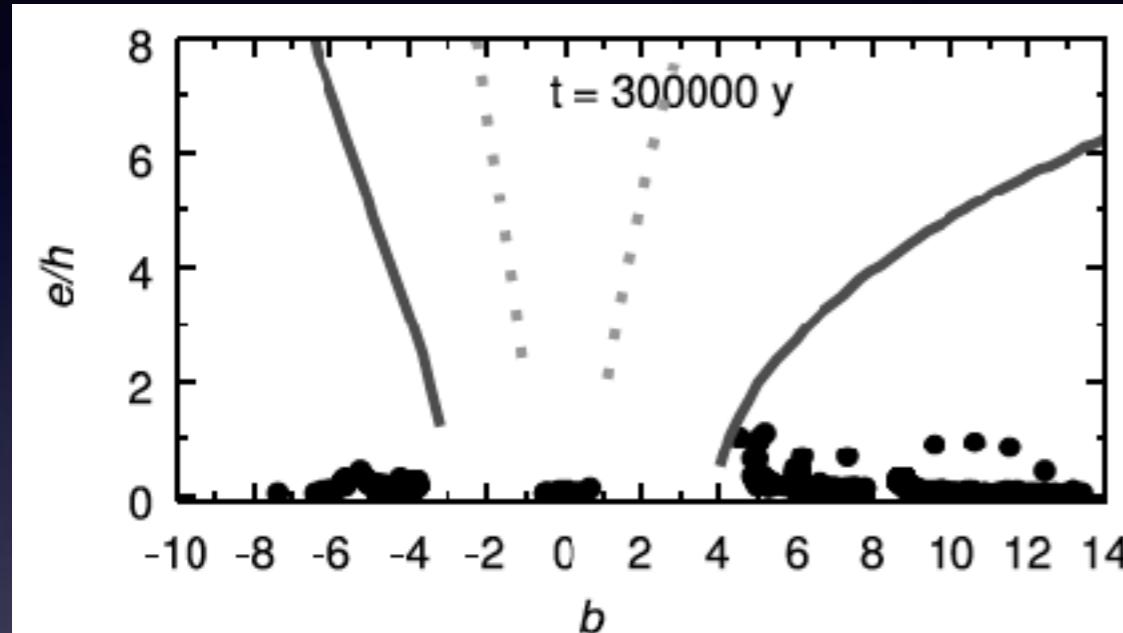
Pebbles

dust in gas

Planetesimal Accretion

$$\frac{dM_{pl}}{dt} \propto M_p^{2/5} \tau_{g,acc}^{-4/5}$$

without planetesimal gaps



$$\frac{dM_{pl}}{dt} \propto M_p^{13/30} \tau_{g,acc}^{-7/5}$$

with planetesimal gaps

$$M_p = M_{XY} + M_Z$$

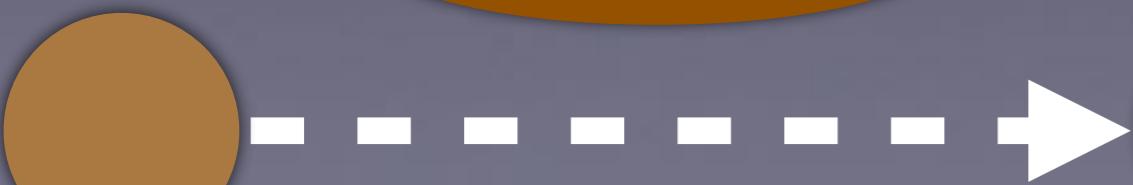
$\tau_{g,acc}$: gas accretion timescale

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$

Planetesimals

Pebbles

dust in gas



Pebble Accretion

The final formation stage is out of the scope of recent studies

$$\frac{dM_{pe}}{dt} \propto M_p^{2/3}$$

the Hill regime is considered

$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$

Planетесimals

Pebbles

dust in gas

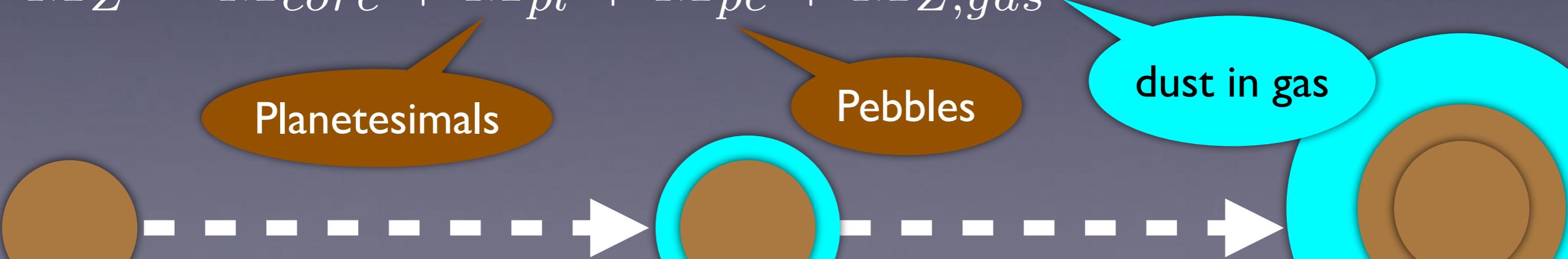


Power-law index	T16	M_{core}	M_{pl} (w/o Gap)	M_{pl} (w/ Gap)	M_{pe}
$\Gamma(M_Z \propto M_p^\Gamma)$	3/5	0	1/3	3/5	1/3
$\beta(Z_p \propto M_p^\beta)$	-2/5	-1	-2/3	-2/5	-2/3

Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007

$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$



Planetsimals

Pebbles

dust in gas

Power-law index	T16	M_{core}	M_{pl} (w/o Gap)	M_{pl} (w/ Gap)	M_{pe}
$\Gamma(M_Z \propto M_p^\Gamma)$	3/5	0	1/3	3/5	1/3
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Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007

Planets accreted solids from **gapped** planetesimal disks
at the **final** formation stage

$$M_p = M_{XY} + M_Z$$

$$M_Z = \cancel{M_{core}} + \circled{M_{pl}} + \cancel{M_{pe}} + M_{Z,gas}$$

Planetesimals

Pebbles

dust in gas



Dust accretion accompanying with gas accretion

$$\begin{aligned}M_{Z,gas} &= Z_s M_{XY} \\&= Z_s (M_p - M_Z)\end{aligned}$$

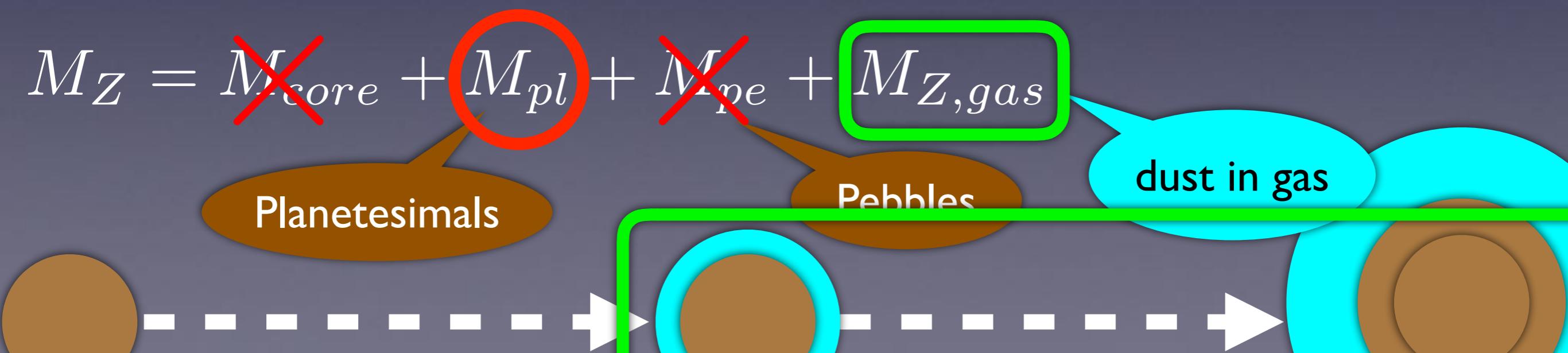
$$M_p = M_{XY} + M_Z$$

$$M_Z = \cancel{M_{core}} + \cancel{M_{pl}} + \cancel{M_{pe}} + M_{Z,gas}$$

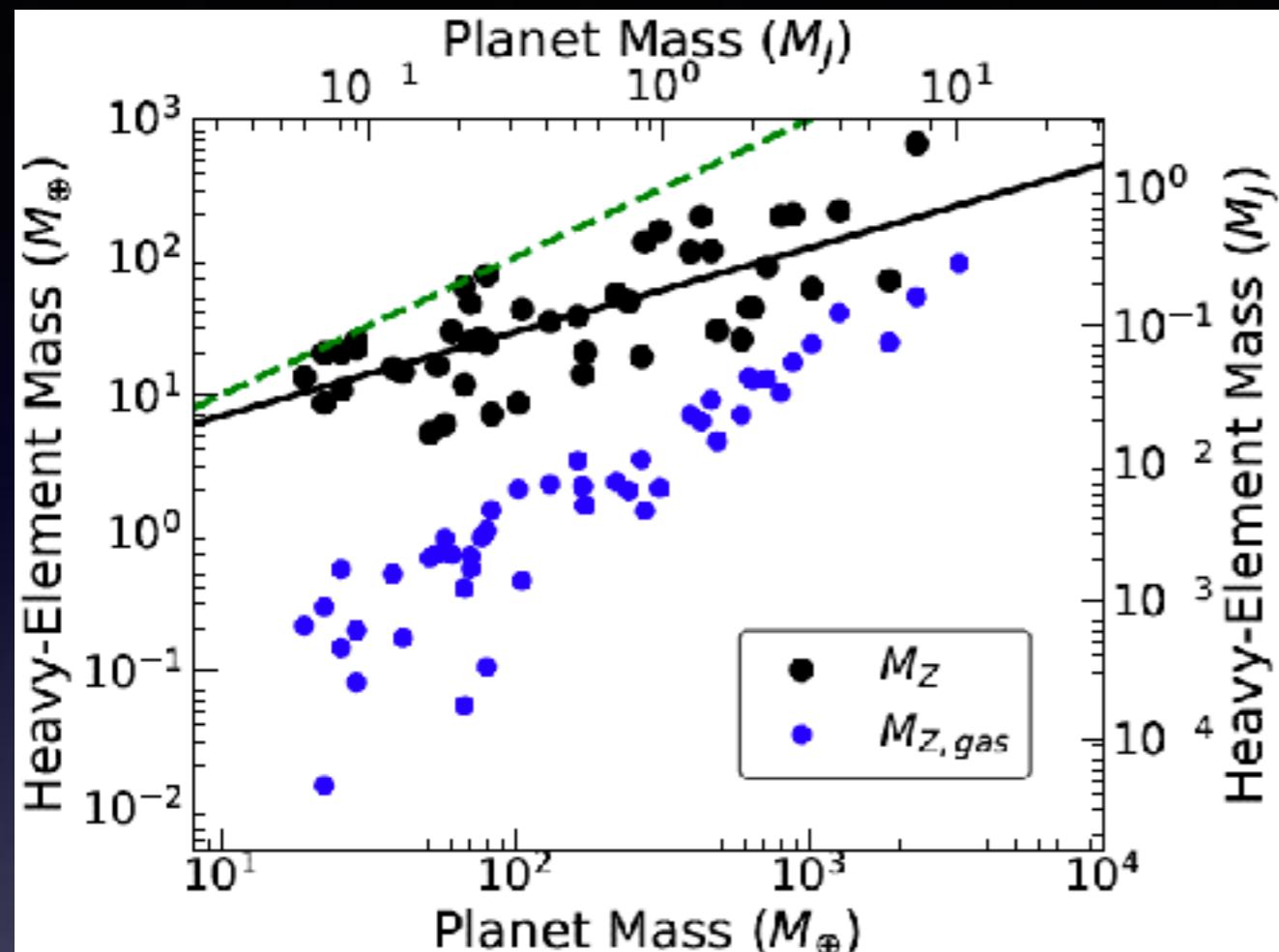
Planetsimals

Pebbles

dust in gas



Dust accretion accompanying with gas accretion



$$M_{Z,gas} = Z_s M_{XY}$$
$$= Z_s (M_p - M_Z)$$

Contribution arising from
gas accretion is negligible

$$M_p = M_{XY} + M_Z$$

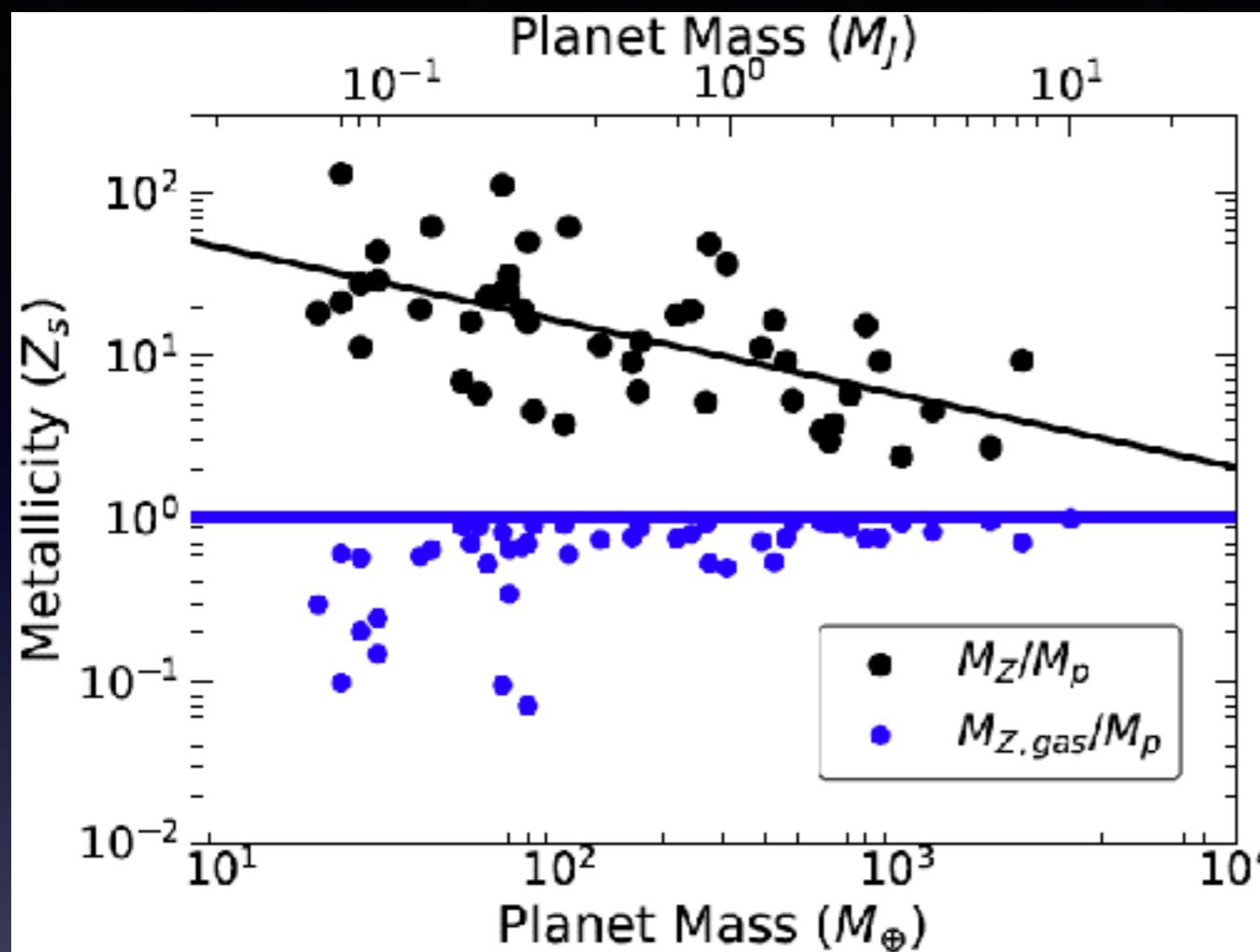
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Planets

Pebbles

dust in gas

Dust accretion accompanying with gas accretion



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Contribution arising from gas accretion is negligible

The dust abundance in the accreted gas is similar to Z_s

$$M_p = M_{XY} + M_Z$$

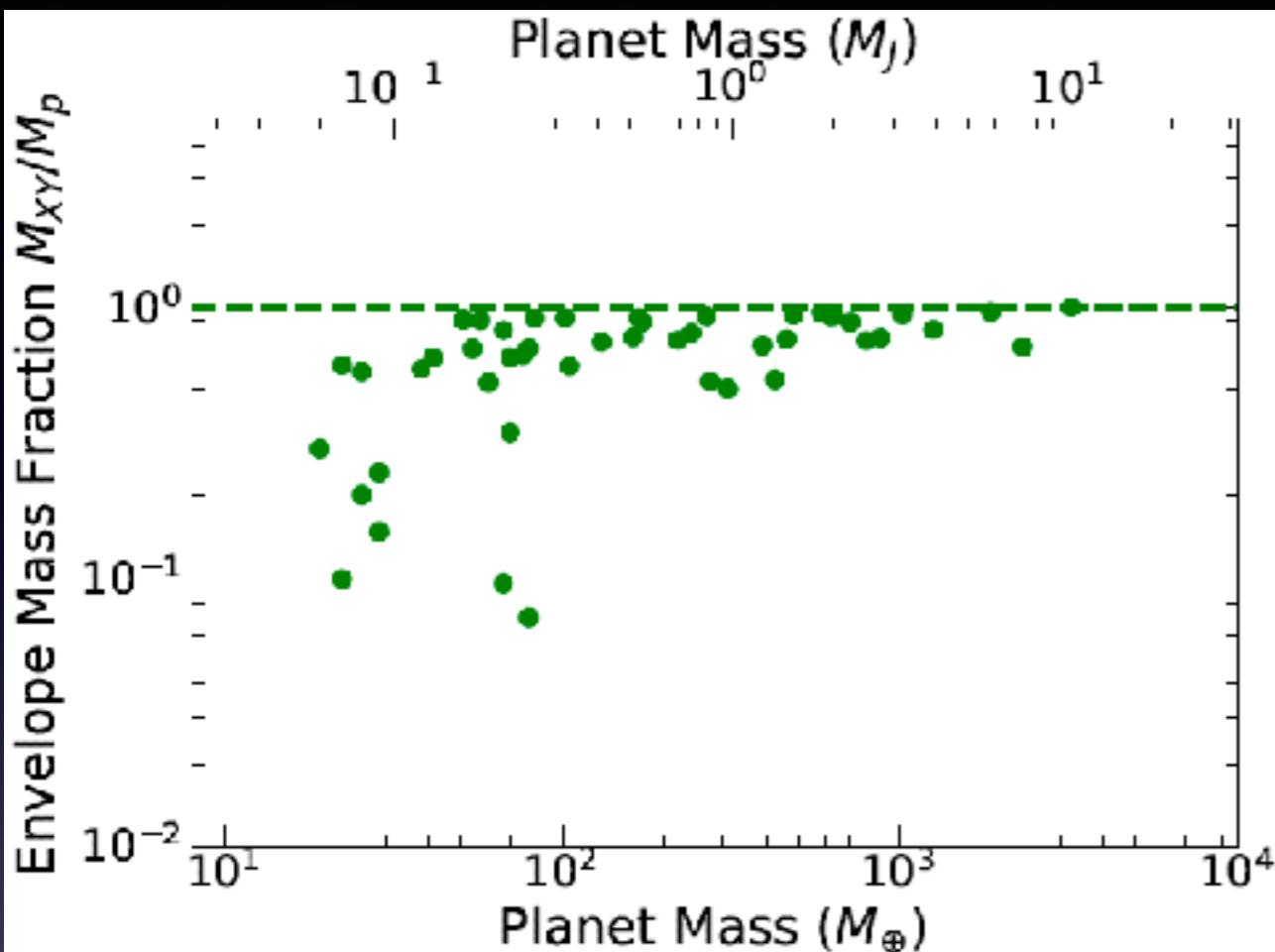
$$M_Z = \cancel{M_{core}} + \cancel{M_{pl}} + \cancel{M_{pe}} + \cancel{M_{Z,gas}}$$

Planets

Pebbles

dust in gas

Critical core mass and runaway gas accretion



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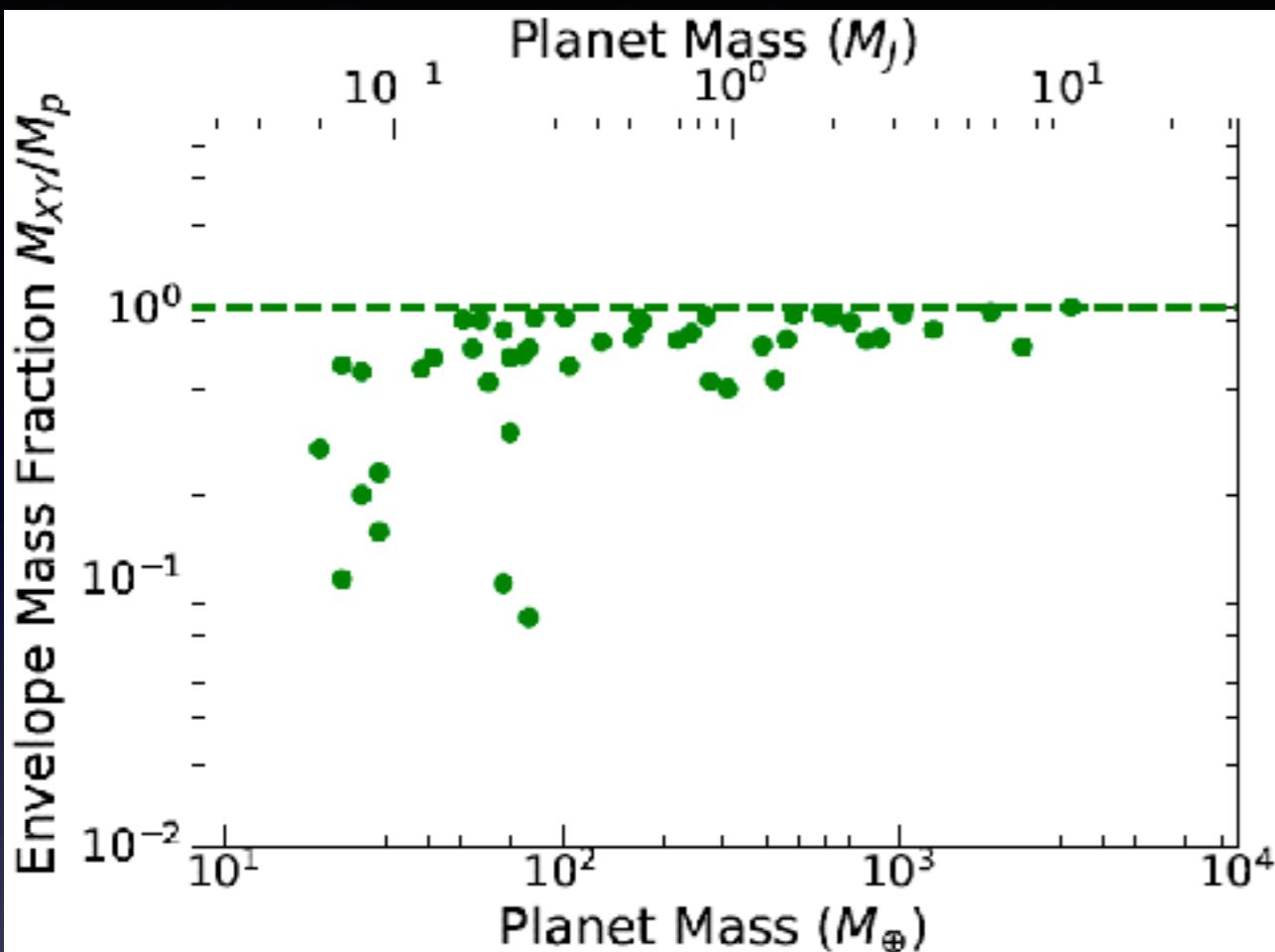
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Planetesimals

Pebbles

dust in gas

Critical core mass and runaway gas accretion



Runaway gas accretion occurred for planets with $M_p > 100M_\odot$

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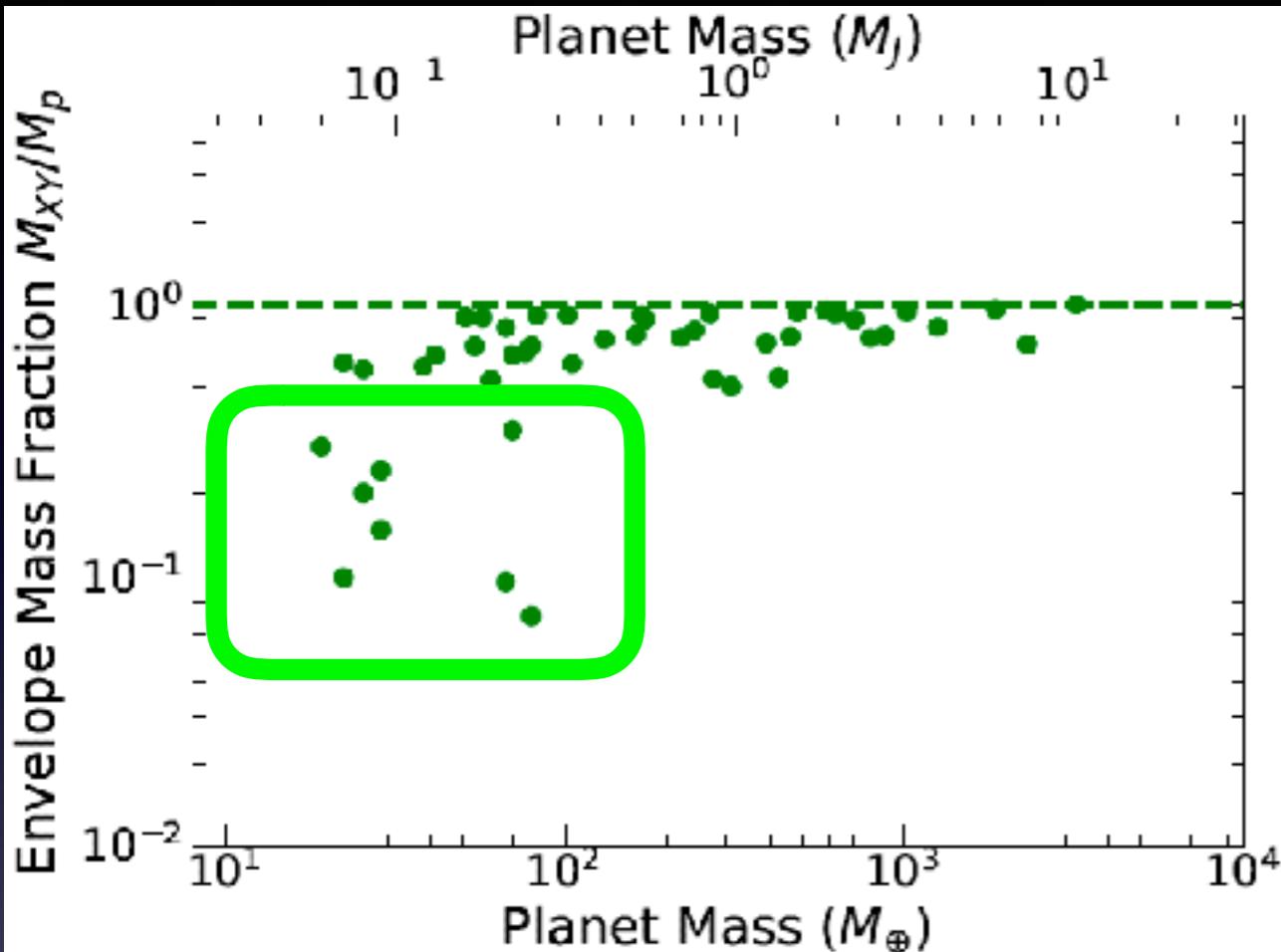
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Planetsimals

Pebbles

dust in gas

Critical core mass and runaway gas accretion



Runaway gas accretion occurred for planets with $M_p > 100 M_{\odot}$

Some mechanisms are needed for some exoplanets to avoid runaway gas accretion

$$M_p = M_{XY} + M_Z$$

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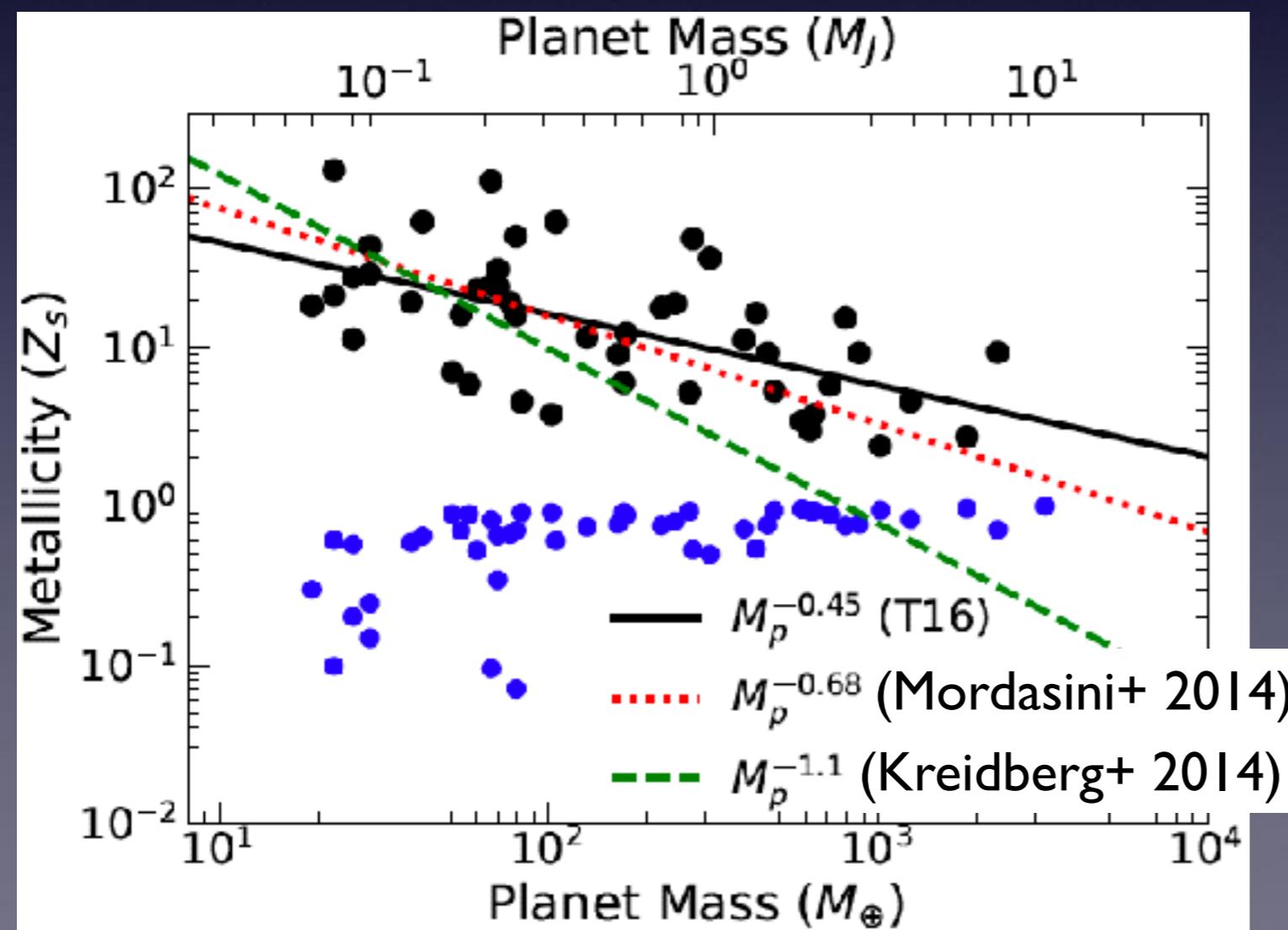
Planетесimals

Pebbles

dust in gas

Power-law index	T16	M_{core}	M_{pl} (w/o Gap)	M_{pl} (w/ Gap)	M_{pe}
$\Gamma(M_Z \propto M_p^\Gamma)$	3/5	0	1/3	3/5	1/3
$\beta(Z_p \propto M_p^\beta)$	-2/5	-1	-2/3	-2/5	-2/3

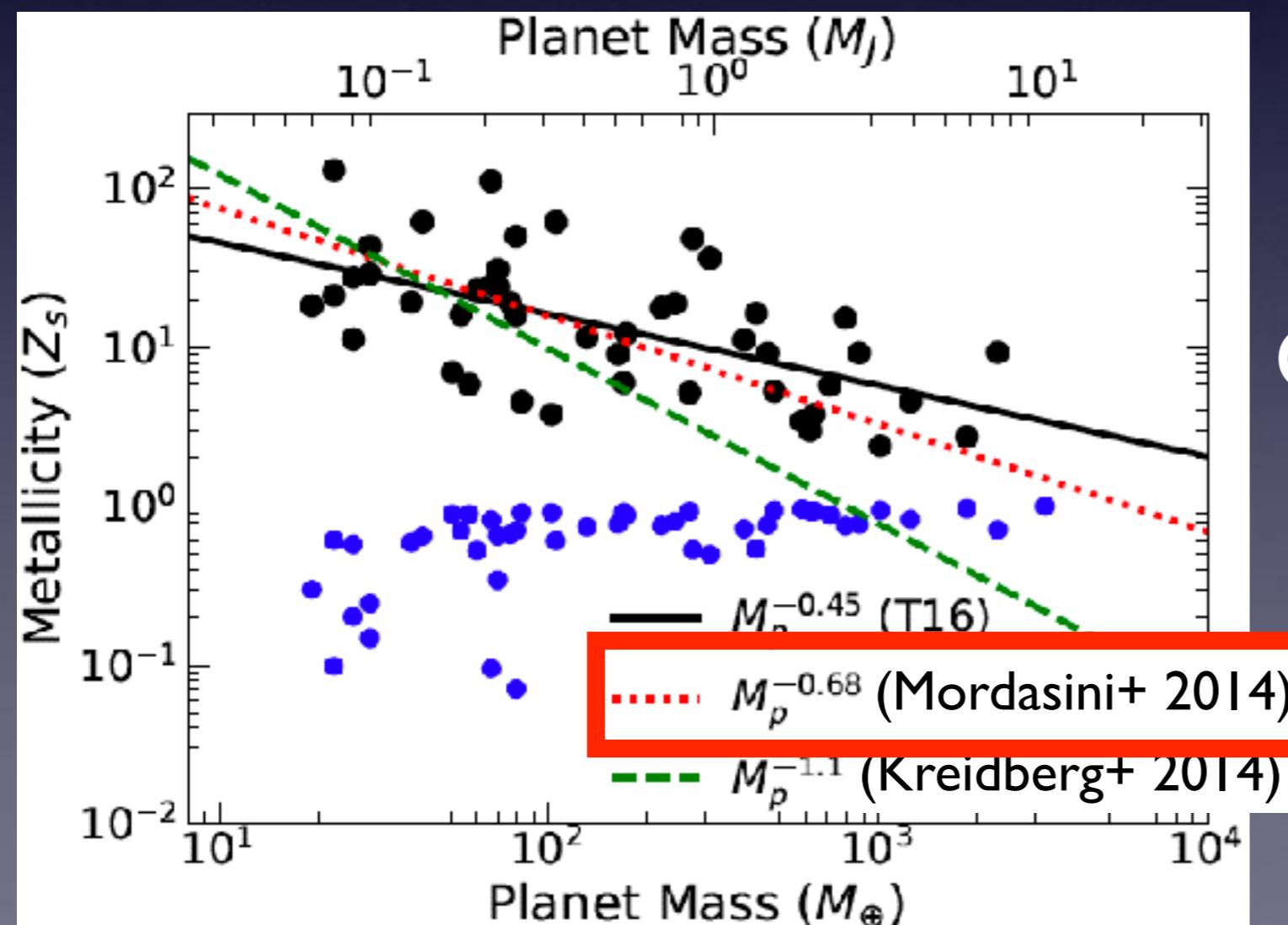
Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007



Comparison with previous studies

Power-law index	T16	M_{core}	$M_{pl} (\text{w/o Gap})$	$M_{pl} (\text{w/ Gap})$	M_{pe}
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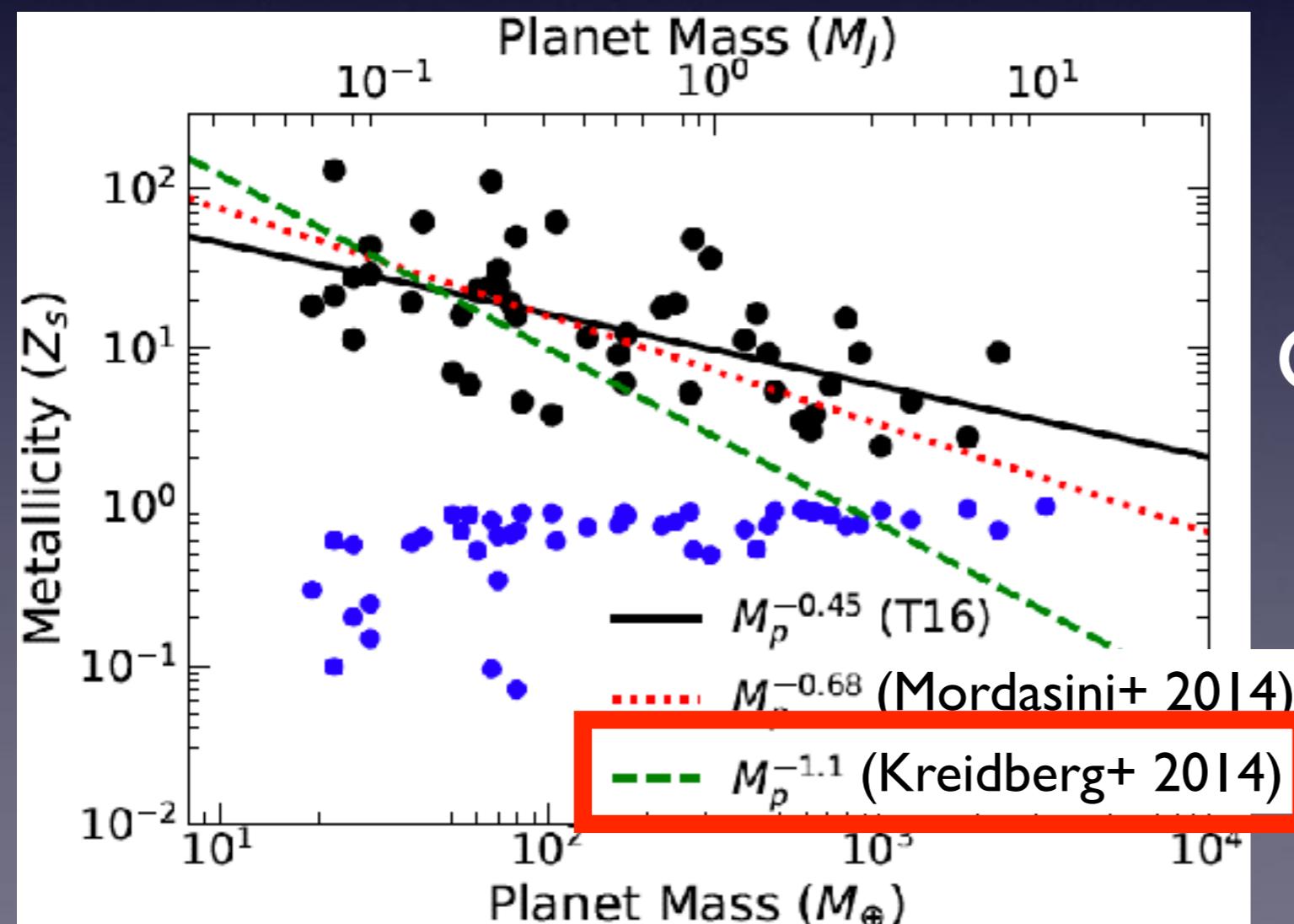


Comparison with previous studies

Our model can reproduce the results of Mordasini

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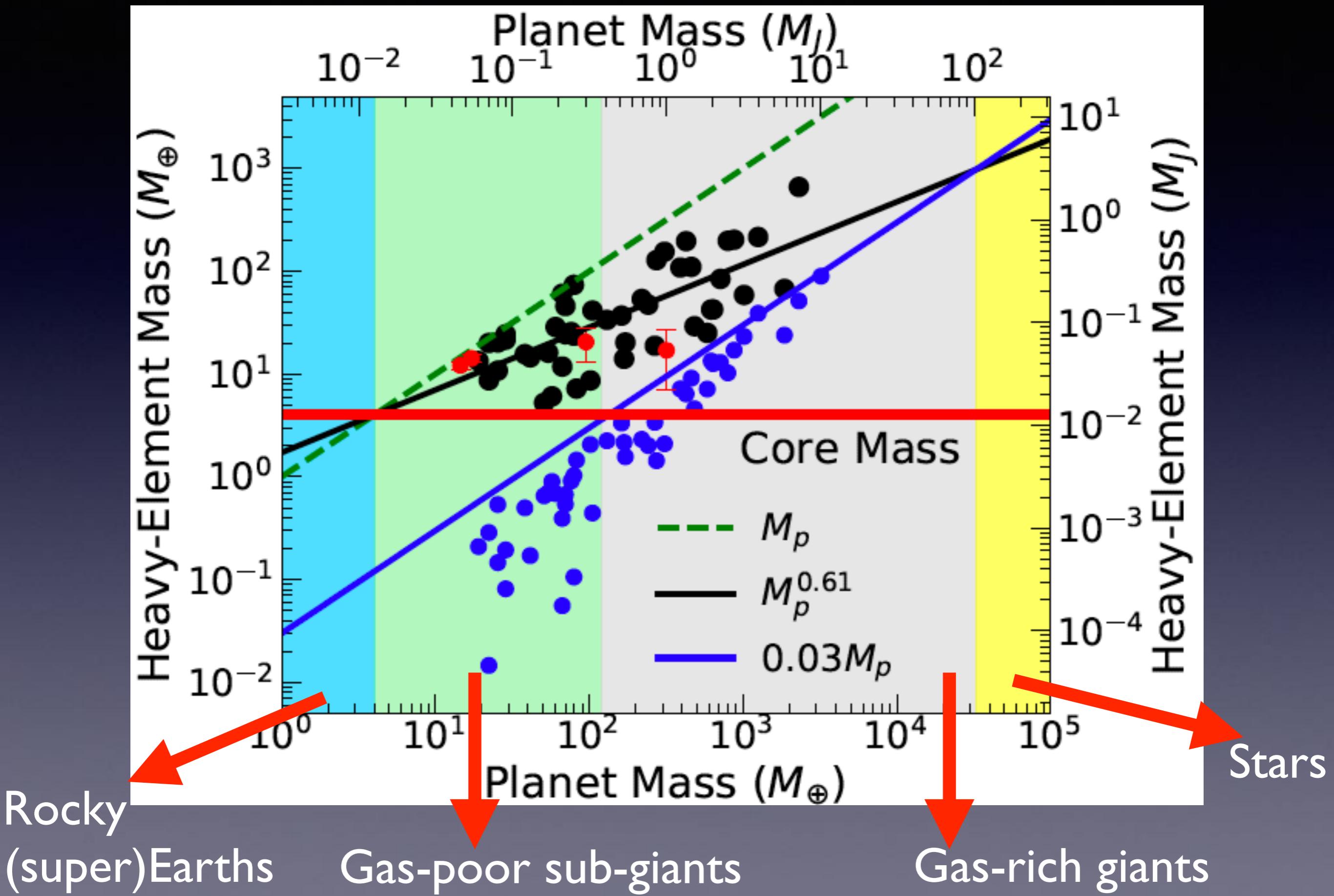


Comparison with previous studies

Our model can reproduce the results of Mordasini

Evolution of atmospheric metallicities in exoplanets can be explored

Classification of observed exoplanets



Summary

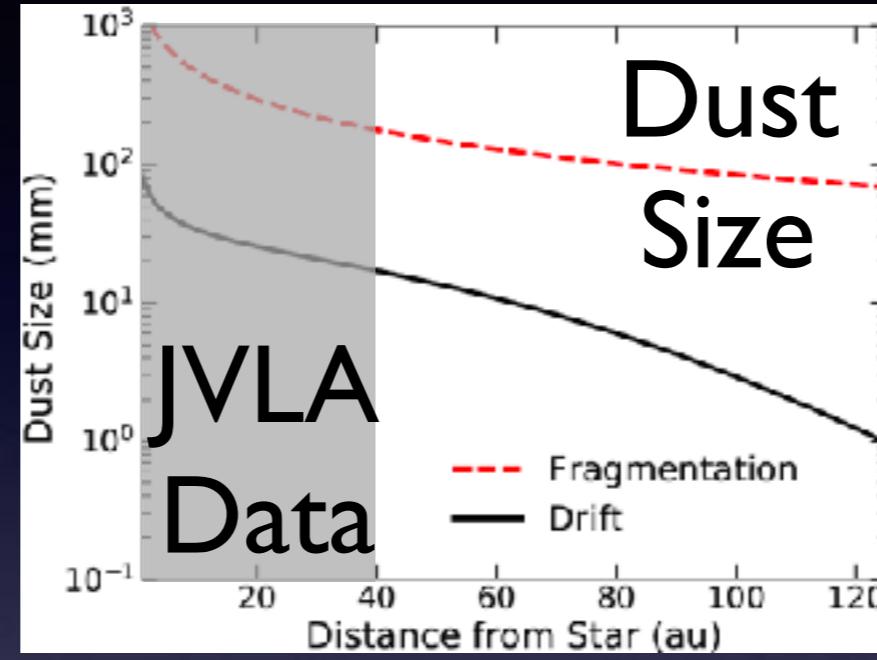
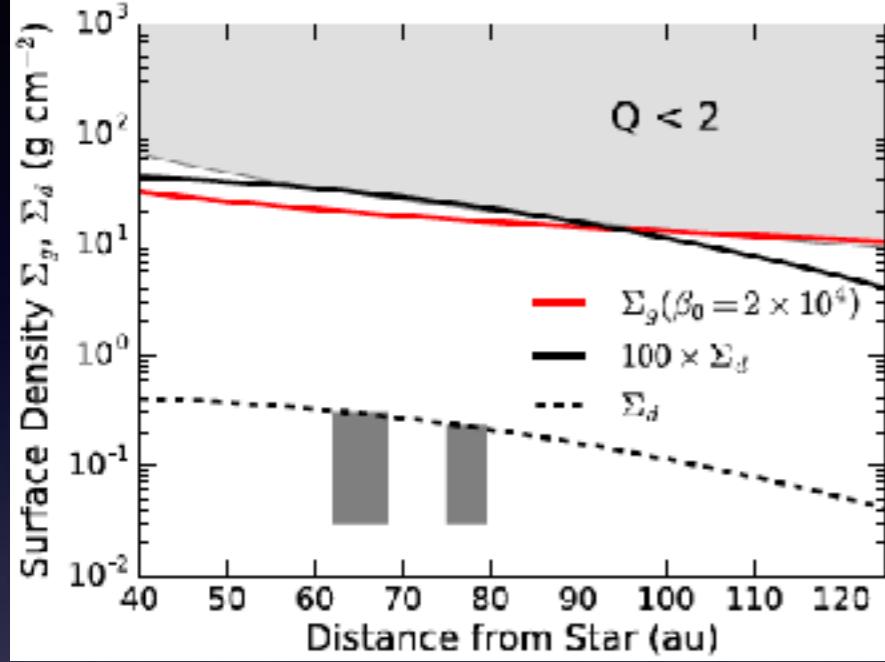
Hasegawa et al. 2018, submitted
(arXiv:1807.05305)

- Observed warm Jupiters tend to have correlations:

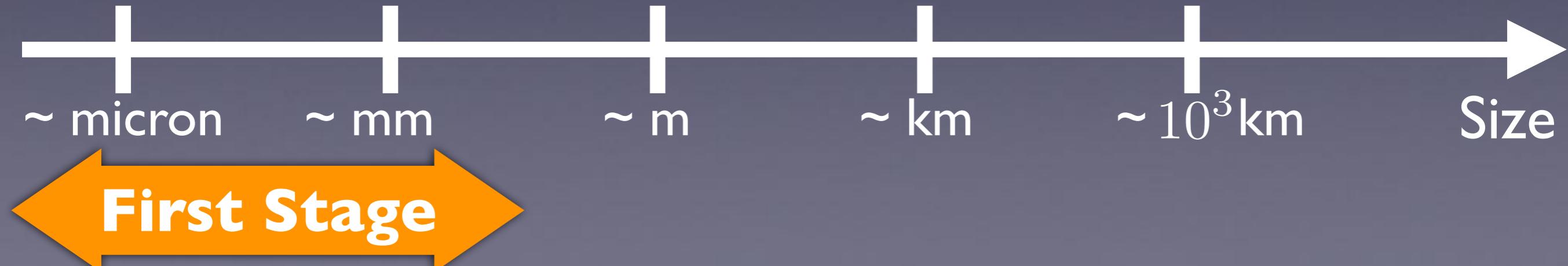
$$M_Z \propto M_p^{3/5} \quad \frac{Z_p}{Z_s} = \frac{M_Z}{M_p} \frac{1}{Z_s} \propto M_p^{-2/5}$$

- We show that accretion of solids from **gapped planetesimal** disks can reproduce the above trends better
- Our results indicate that core formation, pebble accretion, and dust accretion accompanying gas accretion are **not** important
- Runaway gas accretion is **avoided** for some planets with mass of $M_p \simeq 20 - 100 M_\oplus$
- Our analysis can **reproduce** the results of detailed population synthesis calculations (Mordasini et al 2014)
- Our results suggest that evolution of **atmospheric metallicities** can be explored in the $Z_p - M_p$ diagram

Coupling of Disk Observations with Dust Growth Models



We will **specify** the distribution
of planet-forming materials in disks



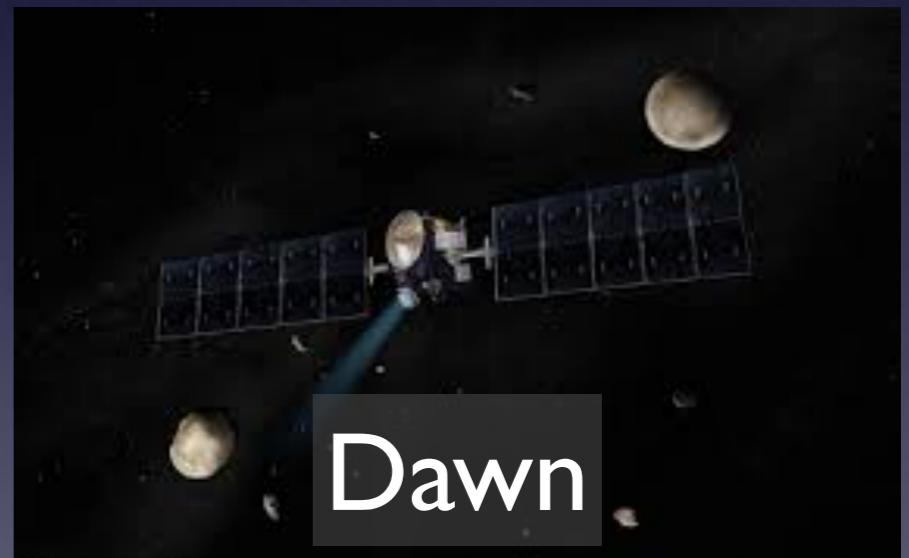
Planetary Formation & Origins of Asteroids

Scenario I: Chondrule accretion



OSIRIS-REx

Scenario 2: Chondrule accumulation



Dawn



WFIRST

Second Stage

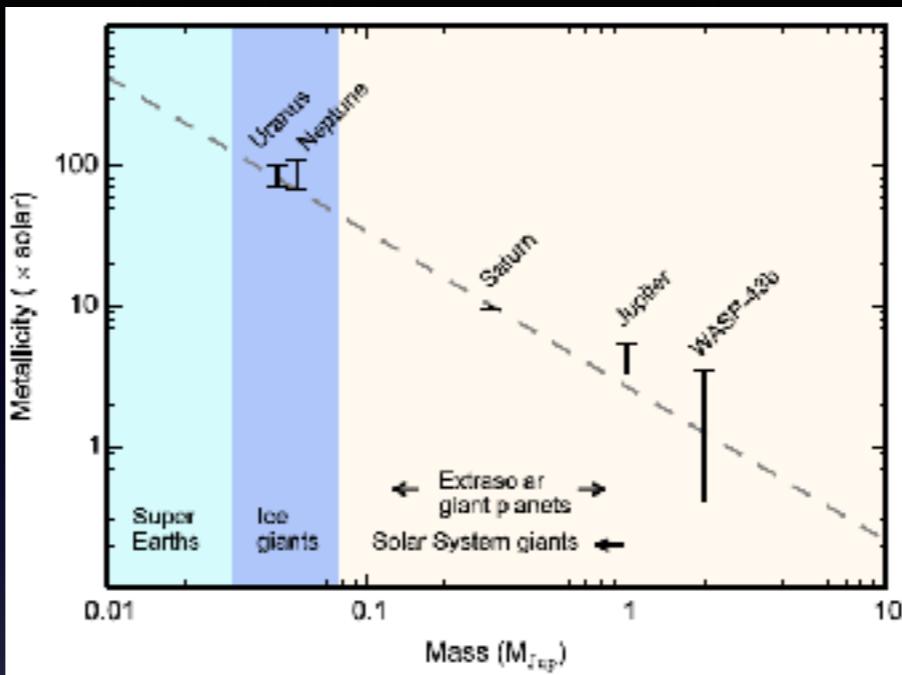
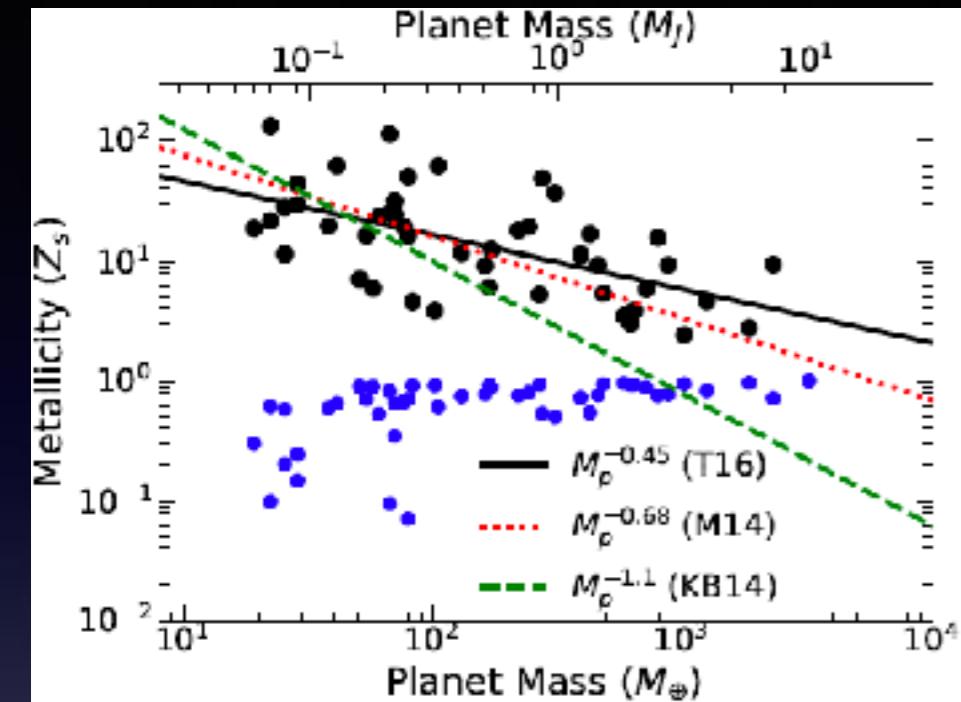
~ m

~ km

~ 10^3 km

Size

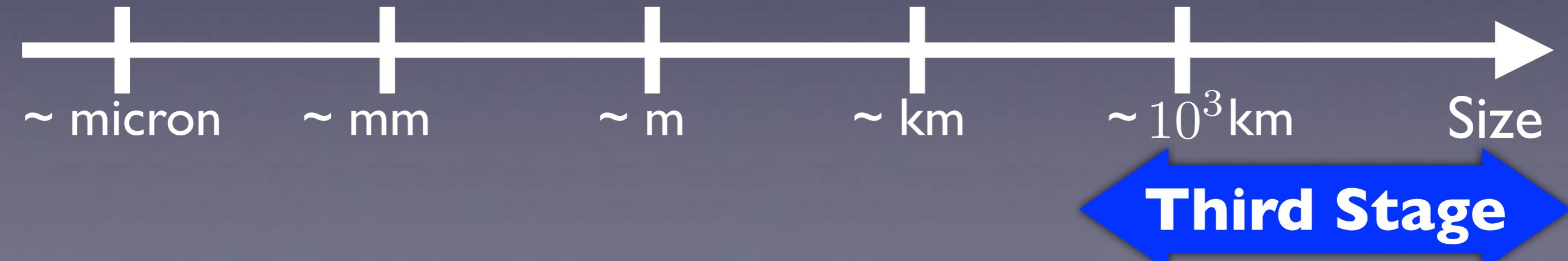
Coupling of Exoplanet Observations with Planet Formation Theory



Hasegawa et al 2018

Kreidberg et al 2014

We will **link** formation mechanisms
of (exo)planets to their atmosphere



Summary

- Planet formation is the long journey from small dust grains to large planets
- A number of important advances in planet formation over full range of scales
- As examples, theoretical modeling of the HL Tau disk and the origin of heavy elements in observed exoplanets are discussed
- further synergies between planetary and exoplanetary sciences will be undertaken to draw a better picture of planet formation and examine the origin of the solar and extrasolar planetary systems